Experimental temperature/velocity control and implications for CFD

Presenters:

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- Russ Fitzgerald, Caterpillar

Participants: All ECN community!

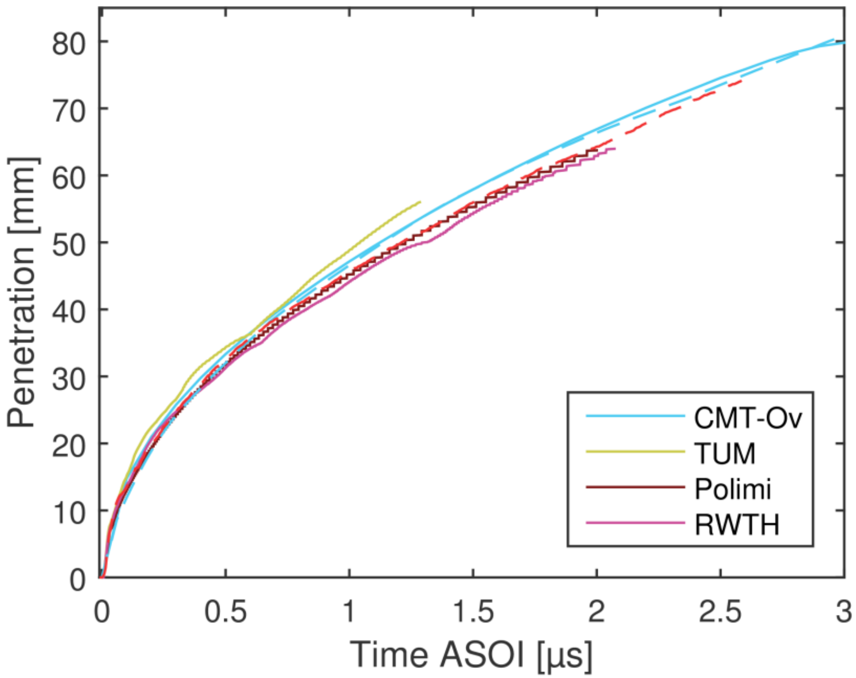
Motivation

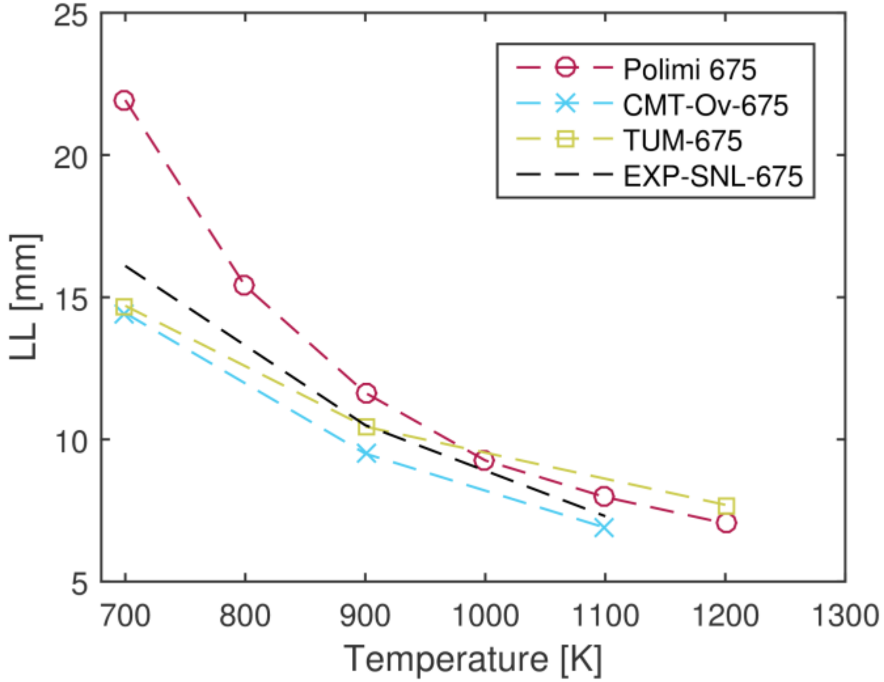
- Do we know the initial conditions for Spray A?
  - What is the temperature distribution?
  - Is aerodynamics experimentally characterized?
  - How these parameters affect the spray results?

- What kind of initial boundary conditions should we use for CFD?

Motivation: Simulation to experiment comparison

VP and LL comparison from Topic 3

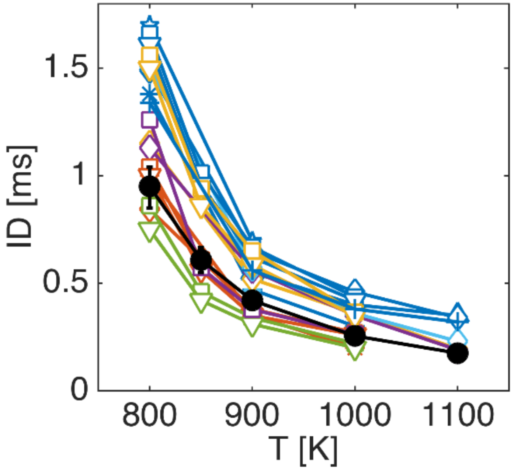


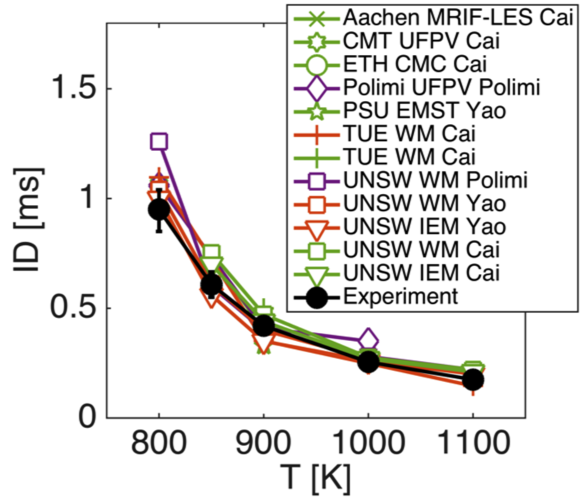


- Small different behavior can be observed when comparing experiments from different ECN facilities
- Simulation is not always perfectly predictive

Motivation: Simulation to experiment comparison

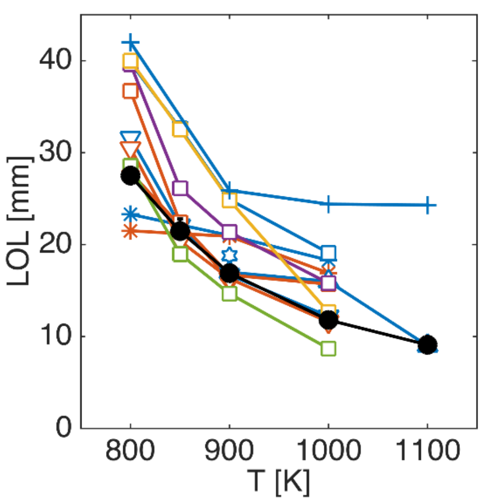
ID and LOL comparison from Topic 4/5

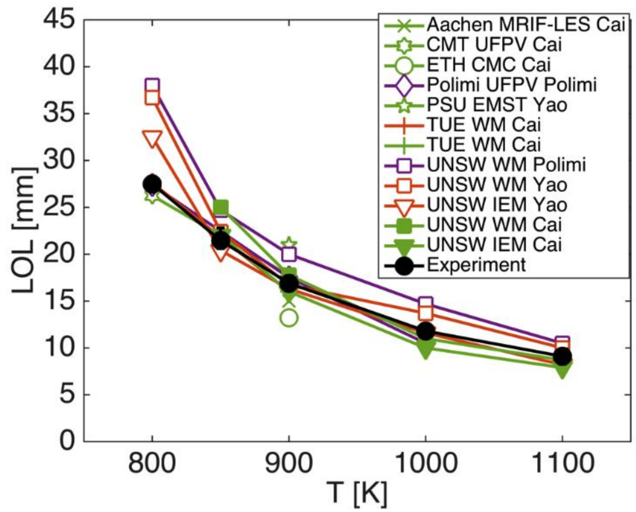




ECN 4

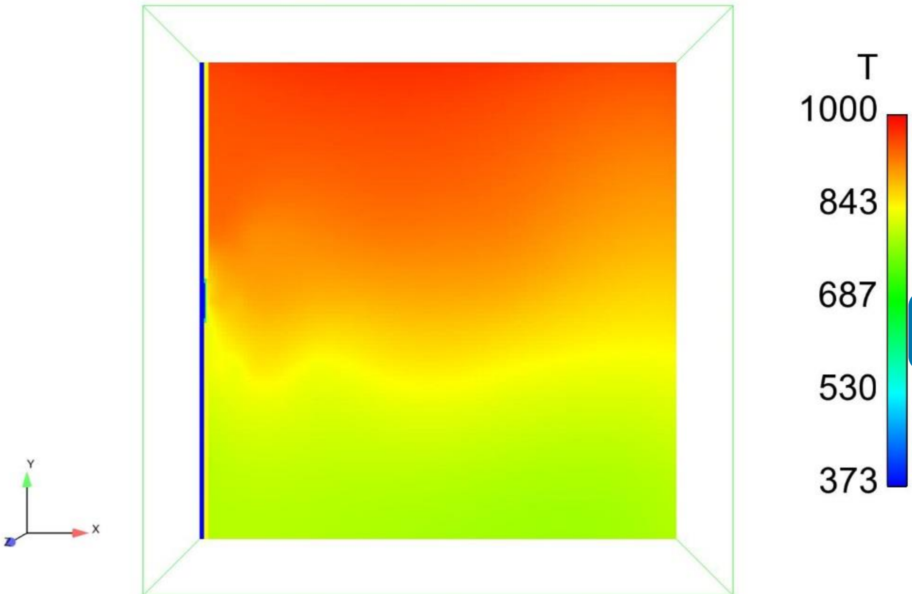
ECN 5

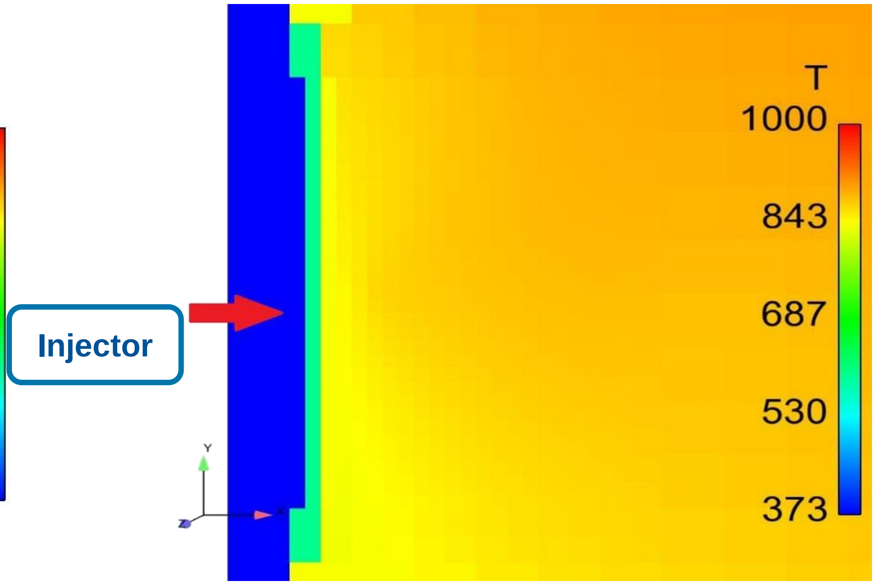




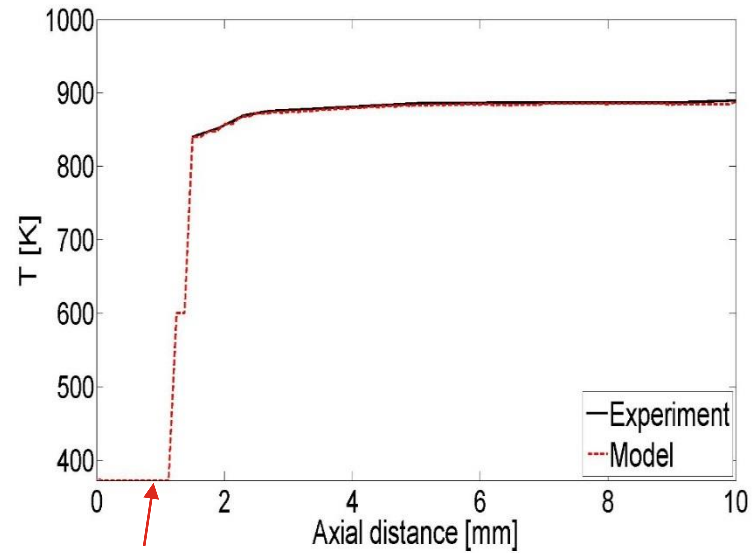
- Under-prediction of shock tube data result in a better match with experimental results
- Simulations use different chemistry and turbulence models
- Simulations are performed with a uniform ambient temperature hypothesis
- What about initial turbulence kinetic energy (not specified by experiments)?
- How does uniform -T and velocity assumptions affect simulation to experiment comparison?

Motivation: Simulation with non-uniform T





- Injector protrudes into vessel 1.1 mm.
- Smallest cell size 0.125 mm.



Injector starts here

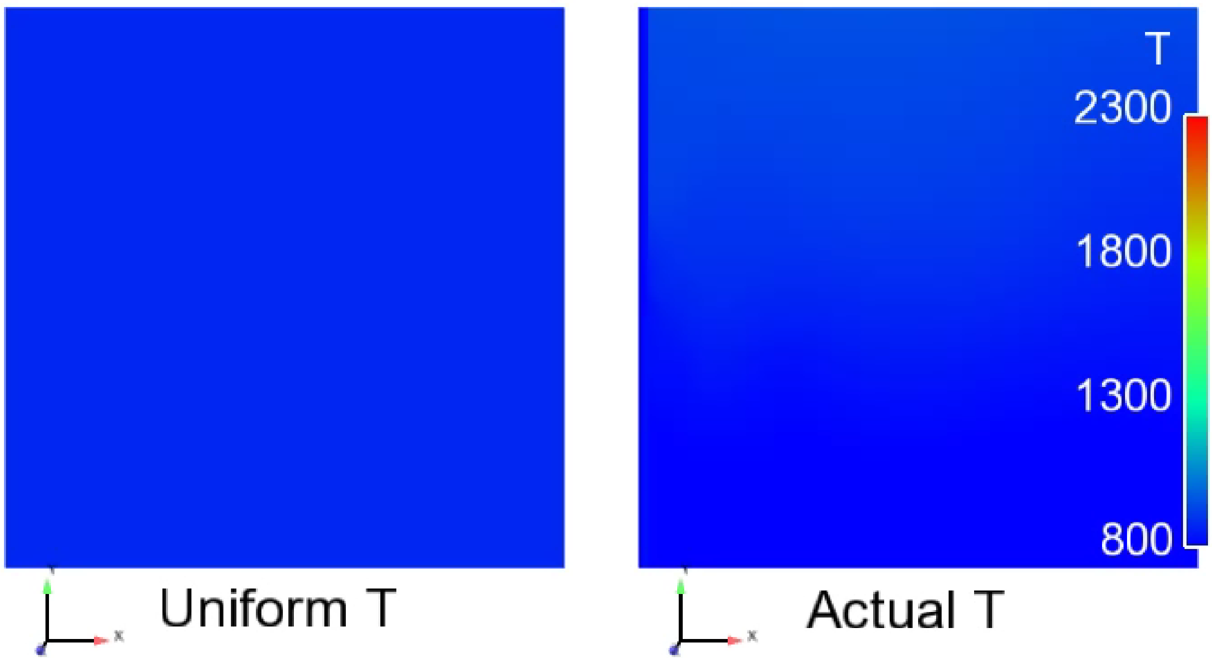
CONVERGE with homogenous-cell chemistry

ECN 3.0 Yuanjiang Pei and Sibendu Som

Motivation: Simulation with non-uniform T

ECN 3.0 Yuanjiang Pei and Sibendu Som

Time = 0.0 ms



- Actual T delays ignition
- Asymmetric flame found in simulation, but not systematically observed in experiments yet (*SAE Paper, 2010-01-2106*)

% change	900 K	1100 K
Liquid length	17.23	27.5
Ignition delay	16.0	6.0
Lift-off length	5.3	8.1

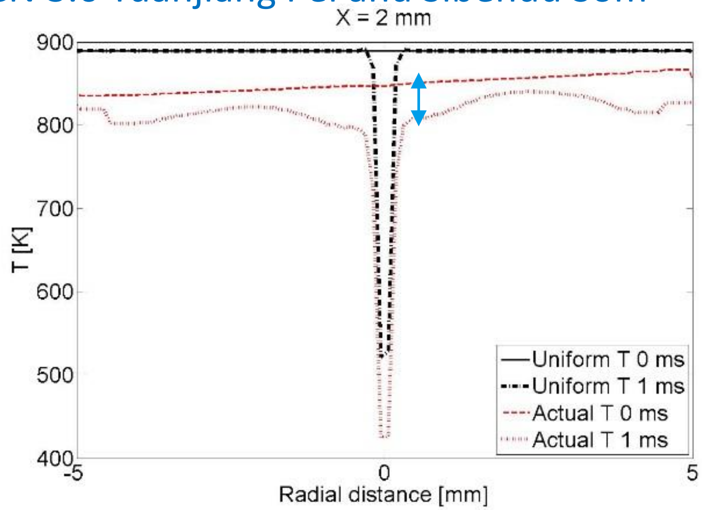
- Retarded ignition will make the ignition delay pedictions even worse in topic 2!

Better chemical mechanism!!

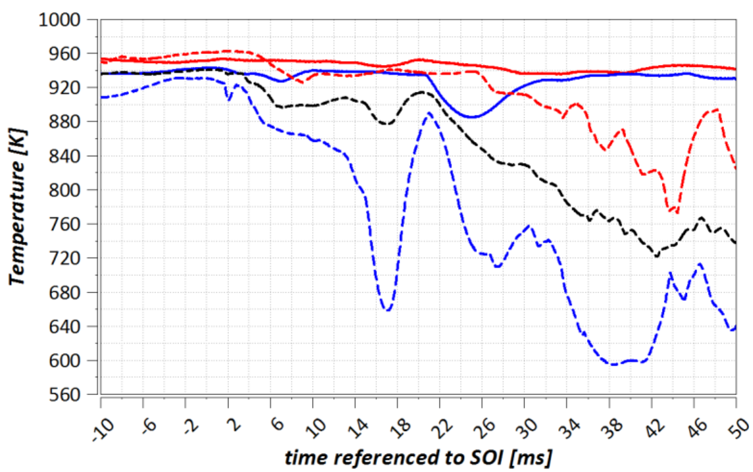
Motivation: Simulation with non-uniform T

Temperature profiles in radial axis: effect of non-uniform T 1 ms after SOI

ECN 3.0 Yuanjiang Pei and Sibendu Som



- At X = 2 mm, T decrease after injection which indicates that colder gas near the boundary layer is pulled in.



Temperature measurement during the injection

(inert condition in the RCM of Pprime Institute)

- Injection aerodynamic bring colder gas into the spray (~43K lower)

Position (X/Y = 0,6/0,3 mm)

7,6µm type K thermocouple

Min Max Average

Without injection With injection

Road Map

- Initial boundary conditions can affect the spray characteristics
  - Review temperature measurement in ECN facilities
  - Collect boundary conditions (temperature and velocity) results from current ECN studies
  - Try to understand their effects on spray and combustion

Discuss new recommendations for ECN spray A

Review of temperature measurement techniques

	Method	Temperature range Min / Max(°C)	Response / transient capability	Accuracy	Commercially available / relative cost
Noninvasive methods	Rayleigh scattering	20 / 2500	Very fast / no	1%	No / very high
	Raman scattering	20 / 2227	Very fast / no	7%	No / very high
	CARS (Coherent Anti-Stokes Raman Scattering)	20 / 2000	Fast / NA	5%	Yes / very high
	LIF (Laser Induced Fluorescence)	0 / 2700	Very fast / no	10%	No / very high
Semi-invasive	Thermographic phosphors	-250 / 2000	Very fast / yes	0,1%-5%	Yes / high

Challenges

CVP

- Minor species in post-preburn => may cause fluorescence quenching

CPF/RCM/RCEM/Engines

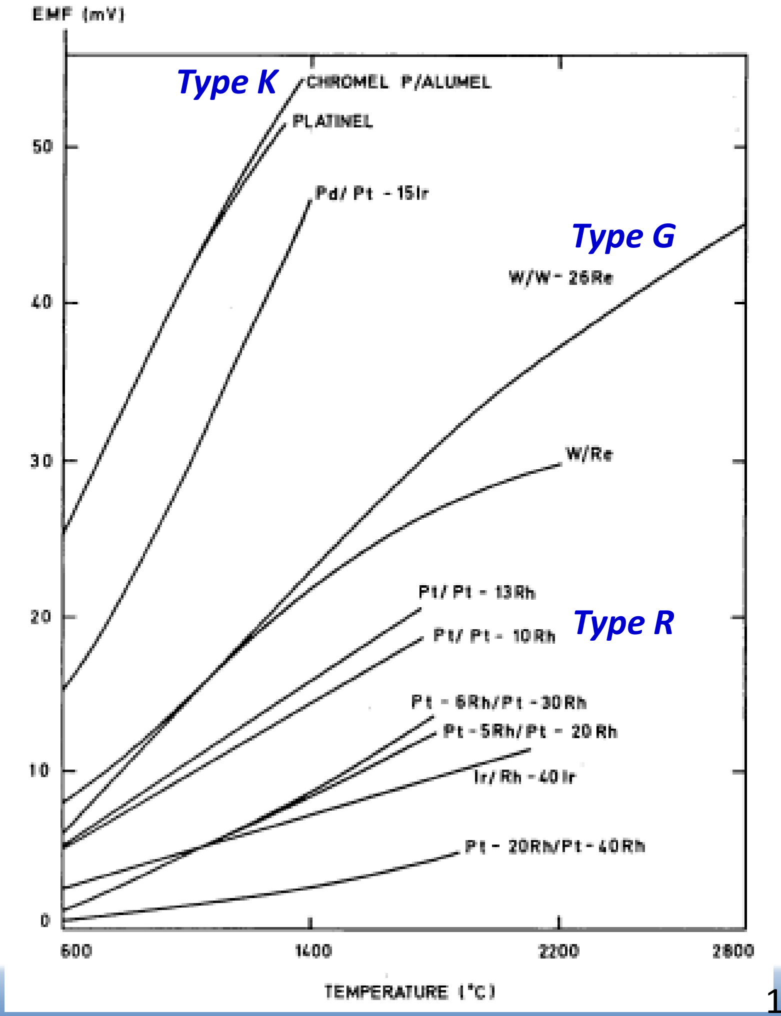
- O_2 quenching
- Low quantum yield at high temperature levels
- Calibration of the technique may be mandatory especially at such high density and temperature levels

Optical methods can provide good spatial and temporal resolution however, they need prior development and a specific calibration for the quantitative measurement => expensive and difficult to install

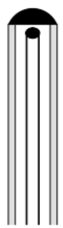
[P.R.N. Childs, J.R. Greenwood and C.A. Long, Review of temperature measurement, Review of scientific instruments, volume71, Number 8, August 2000]

Invasive method	Temperature range Min / Max(°C)	Response / transient capability	Accuracy	Commercially available / relative cost
Thermocouple	-270 / 2300	Very fast / yes	±0.5-±2°C	Yes / very low

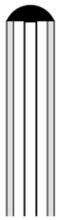
- Thermocouples are cost-effective and accurate temperature sensors
- Can be used in all ECN combustion facilities
- Thermocouples might have a catalytic effect in oxidizing environment (type R for instance)
- Thermocouples might be altered by oxidation (this can have a significant effect on emissivity)



Sheathed thermocouples



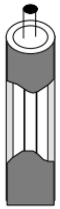
UNGROUNDED JUNCTION



GROUNDED JUNCTION

+ long lifespan (minimized long term drift under cycling conditions)
+ wires protected : can be used in corrosive environment with flowing materials (high robustness)
- Slow response time

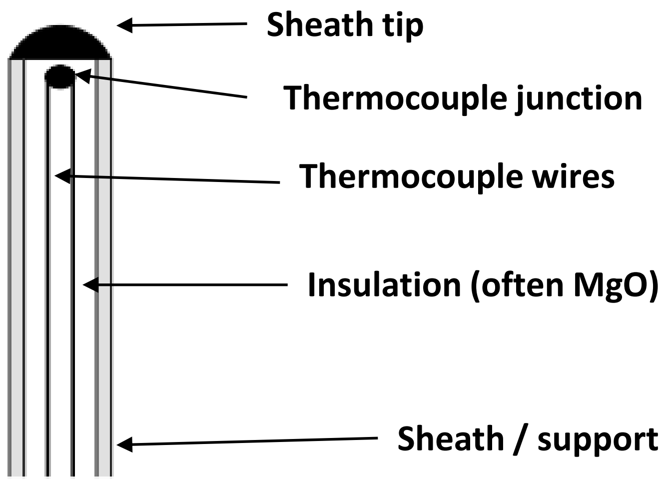
Bare-bead thermocouples



EXPOSED JUNCTION

+ junction isolated from ground (avoid interference with instruments)
+ faster response time
- shorter lifespan
- Inherently brittle

Ungrounded junction	Grounded junction
junction protected	difference in thermal expansion between the sheath and junction materials may cause severe mechanical stress
junction isolated from ground	Ground loops may cause interference with instruments
defects in insulation may be easily detected	are more difficult to detect
slow response time	faster response time



Sheathed thermocouple with ungrounded junction

The magnesium oxide has a high dielectric strength, responds quickly to temperature changes, and is very durable

Measurements are not resolved in space and time

Why is response time too slow?

Measured temperature Tj depend on heat conduction from the sheath to the junction through the insulation and the thermocouple wires => thermal inertia does not only depend on the size of the junction but on the ensemble {sheath (s), insulation (i), junction(j) and wires (w) }

Such thermocouple are intended to measure temperature under steady state conditions

In such configuration, thermal conduction in the axial direction of the sheath has a significant impact on measured temperature Assuming that heat transfer is purely in the axial direction under steady state conditions, the axial heat flow may be modeled: λ is thermal conductivity and A is cross sectional area

$$Q_x = -\widetilde{\lambda A}\,\frac{dT}{dx}$$

$$\widetilde{\lambda A} = \lambda_w A_w + \lambda_i A_i + \lambda_s A_s$$

Response compensation of fine wire thermocouples

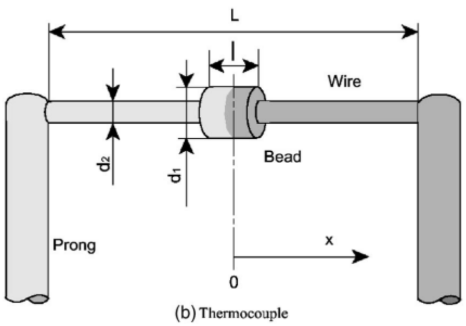


FIG. 1. Sensor configuration and coordinates.

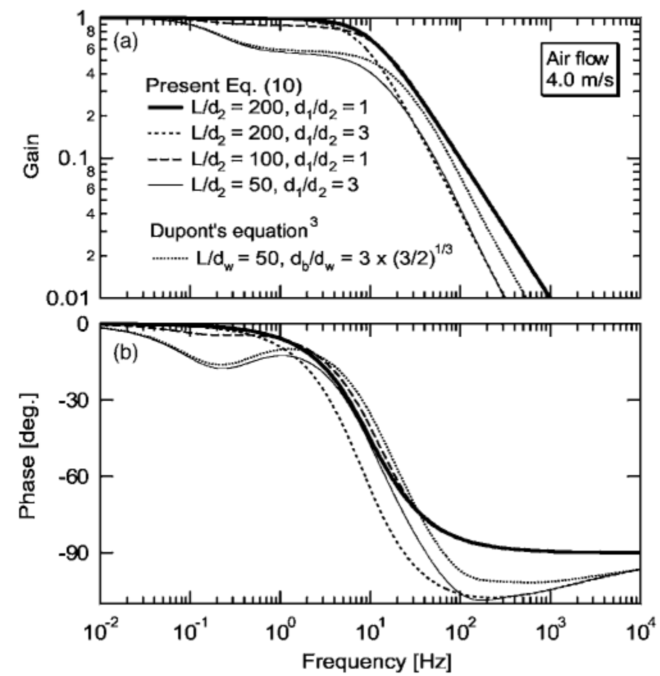
Schematic of bare-bead ungrounded fine wire thermocouple

Hypothesis:

- Fine wires: temperature radially homogeneous => conduction is considered in axial direction x (for instance when T prongs is lower than T wires)
- Heat transfer through: catalytic reactions on the junction, viscous dissipation and thermoelectric effects are neglected

The frequency response of such thermocouple configuration is extensively modeled in literature (energy balance + temperature expressed as Fourier integrals)

Recommendations to minimize conduction effects:
$L >> d_2$ and $d_2 = d_1$



Simulated frequency response of a 25µm type K thermocouple with various probe configurations

Recommendations for the thermocouples design

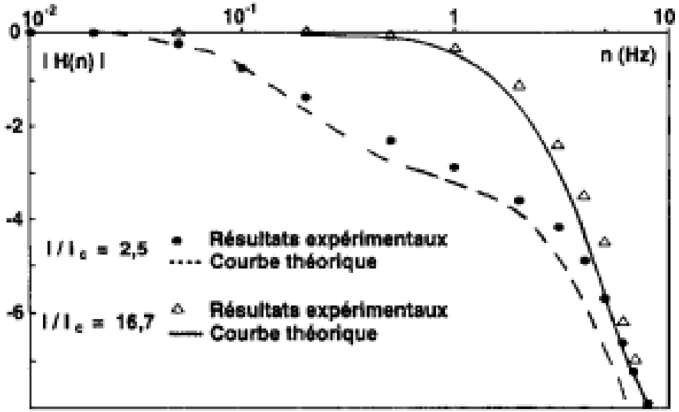


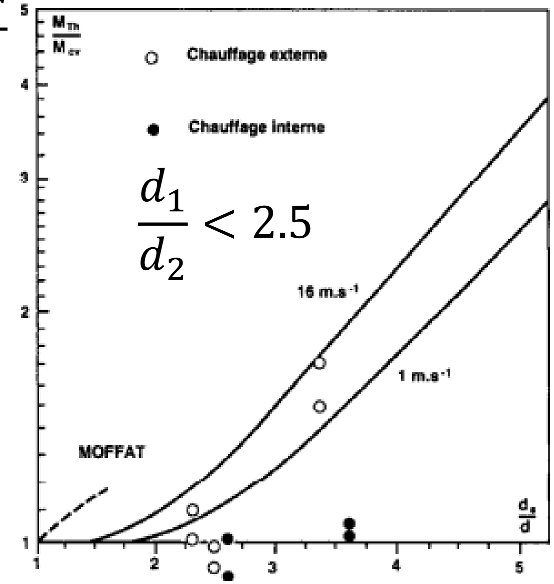
Fig. 21. – Effect of conduction on thermocouple amplitude transfer function. Theoretical predictions are deduced from relation (82)

Cooled length, introduced by Betchov and Corrsin

$$\ell_c = \frac{d}{2}\sqrt{\frac{\lambda_w}{\lambda_g\ Nu}}$$

$$\frac{L}{l_c} > 10 \quad \approx \quad \frac{L}{d_2} \geq 400$$

$$\frac{\tau_{seensor}}{\tau_{wire}}$$



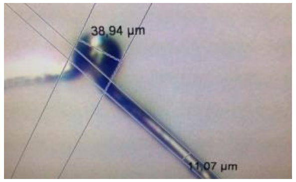
$$\frac{d_1}{d_2} < 2.5$$

$$\frac{d_1}{d_2}$$

Fig. 20. – Comparison between predicted and measured thermocouple time constants using external and internal heating techniques. Experimental points correspond to values measured at 1 m.s^{-1} and 15 m.s^{-1}. Theoretical predictions are deduced from relation (81)

d_1 and d_2 as small as possible

TU/e, type R
d_w = 50 µm
d_j = 100 µm



Prisme (Orleans, France), type K
d_w = 13 µm
d_j = 39 µm

Pprime (Poitiers, France), type K
d_w = 7.6 µm
d_j = ~ 8 to 14 µm

[Paranthoën and Lecordier, Mesures de température dans les écoulements turbulents, Rev Gén Therm, (1996) 35, 283-308]

Review of error correction / response compensation

$$T_g = T_j + \tau \frac{dT_j}{dt} + \frac{\sigma\varepsilon}{h}\left(T_j^4 - T_s^4\right) \qquad \tau = \frac{\rho_j C_j d_j}{4h}$$

Collis and Williams for 0.02 < Re < 44:

$$Nu = \left(0.24 + 0.51Re^{0.45}\right)\left(\frac{T_f}{T_g}\right)^{0.17} \qquad T_f = \frac{T_j + T_g}{2} \qquad h = \frac{Nu\lambda_g}{d}$$

$C_j = f(T_j)$ and ***$\varepsilon = f(T_j)$***

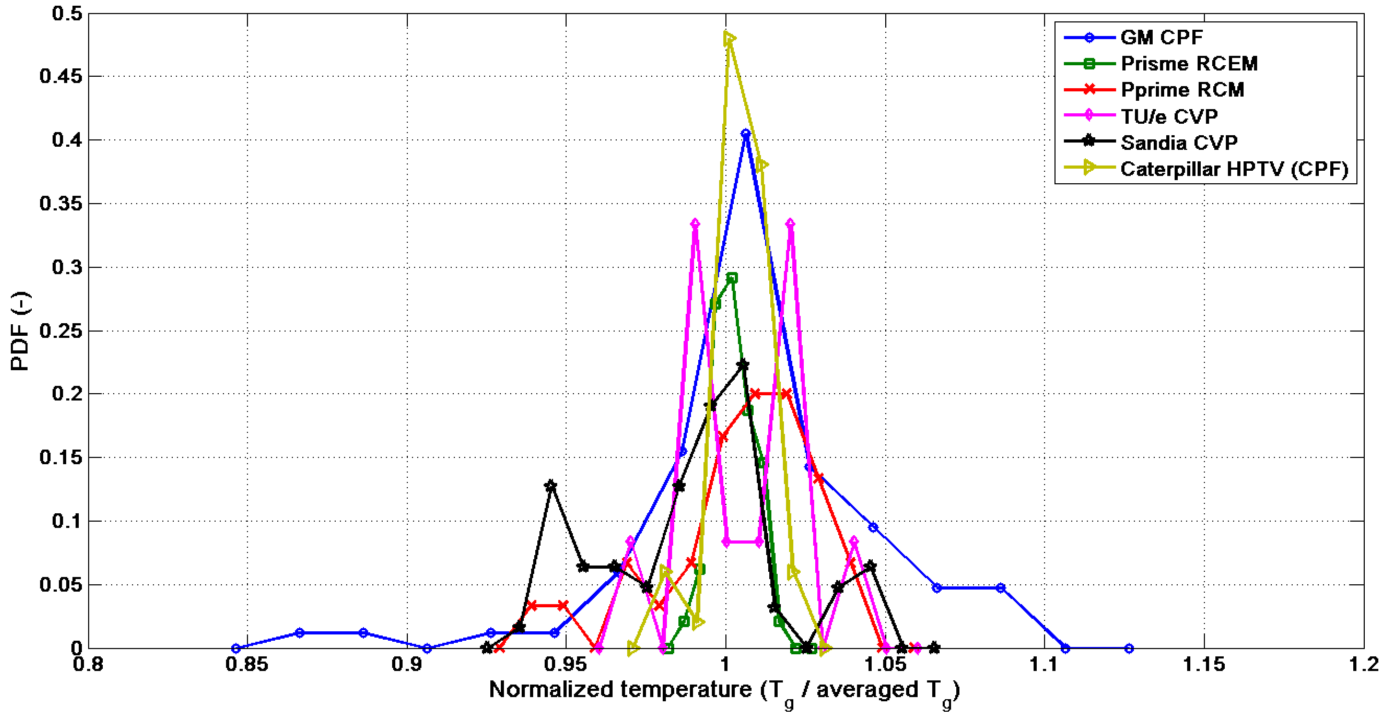
$h = f(T_f, \rho_f, V)$; thermal conductivity and dynamic viscosity of surrounding gas at film temperature T_f

Main issue is to find a good estimation of the cross flow velocity through the junction

- Using a 12,7 µm wire instead of 7,6 µm double the correction (measured temperature increase rate ~17,6 K/ms)
- 1 m/s under-estimation of velocity => 6 K higher correction (example of a type K 12,7µm wire thermocouple, measured temperature increase rate ~17,8 K/ms)
- 1000 W/m².K under-estimation of h (heat coefficient) => 2 K higher correction (example of a type K 12,7µm wire thermocouple, measured temperature increase rate ~17,6 K/ms)

Spatial heterogeneities

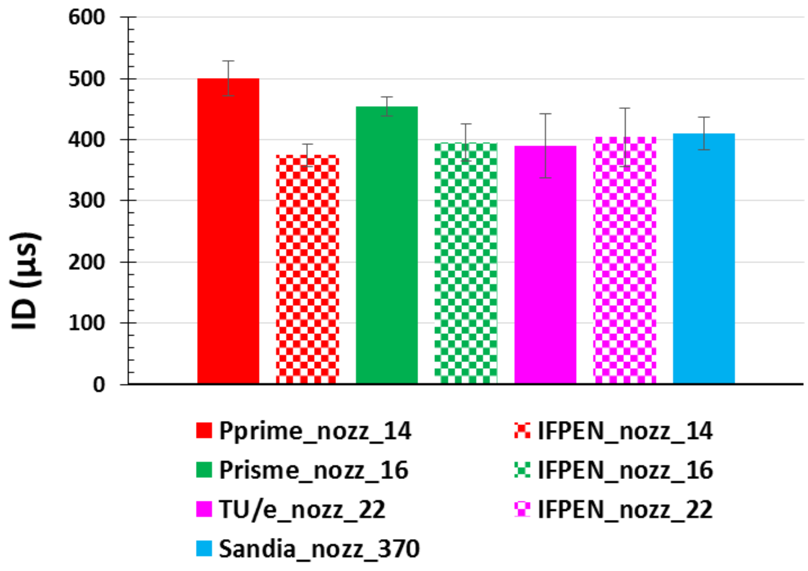
Spatial heterogeneities from available data

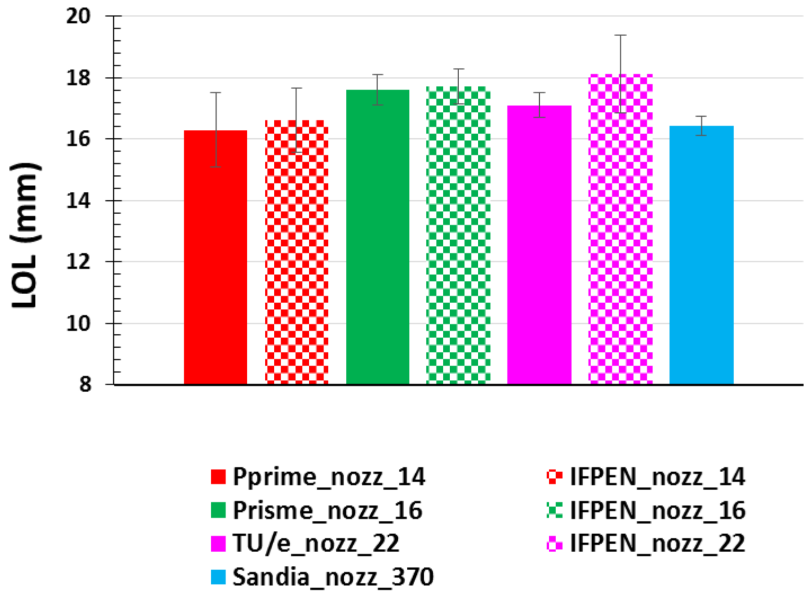


- Temperature heterogeneities are observed in all facilities
- How to calculate the density ?

[Sandia data are presented by distribution of Tcore measured/Tcore_predicted]

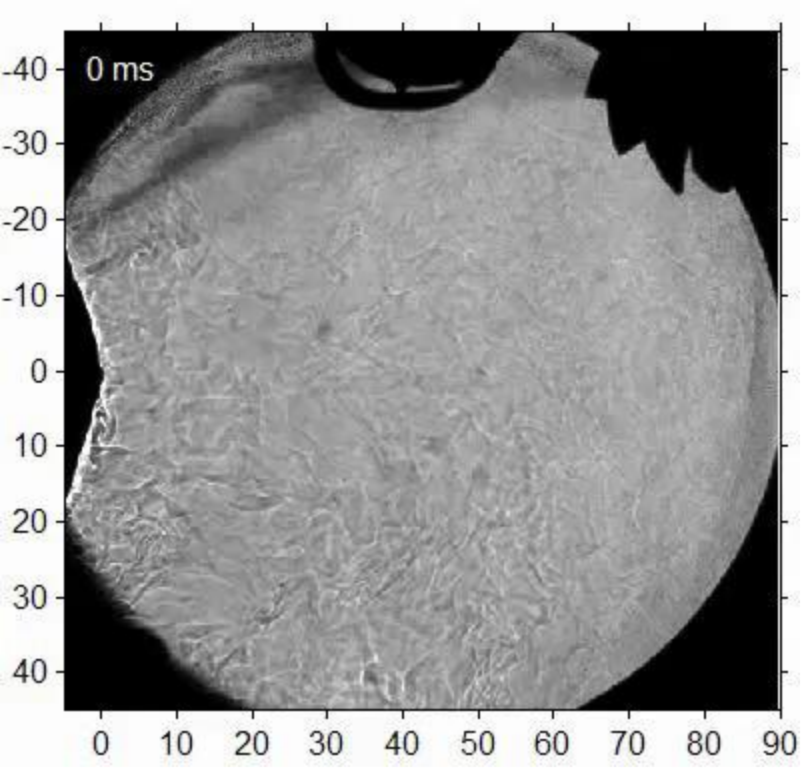
Spray A ID and LOL results

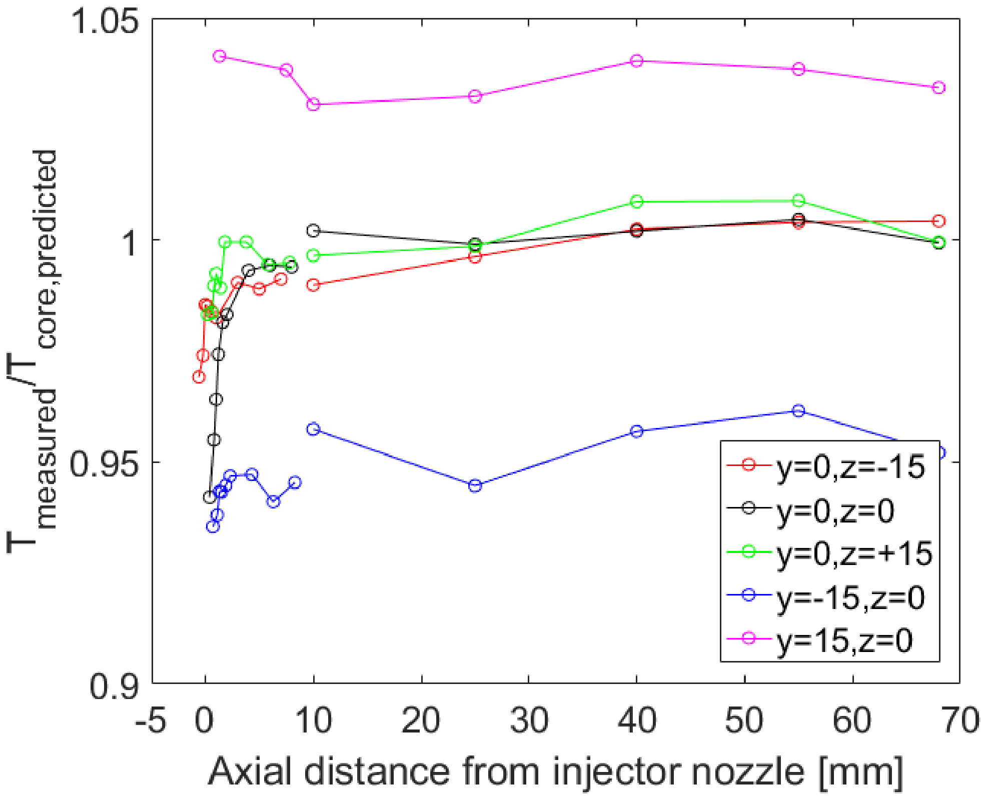




Prisme and Pprime: RCM
Sandia, IFPEN, TU/e: CVP

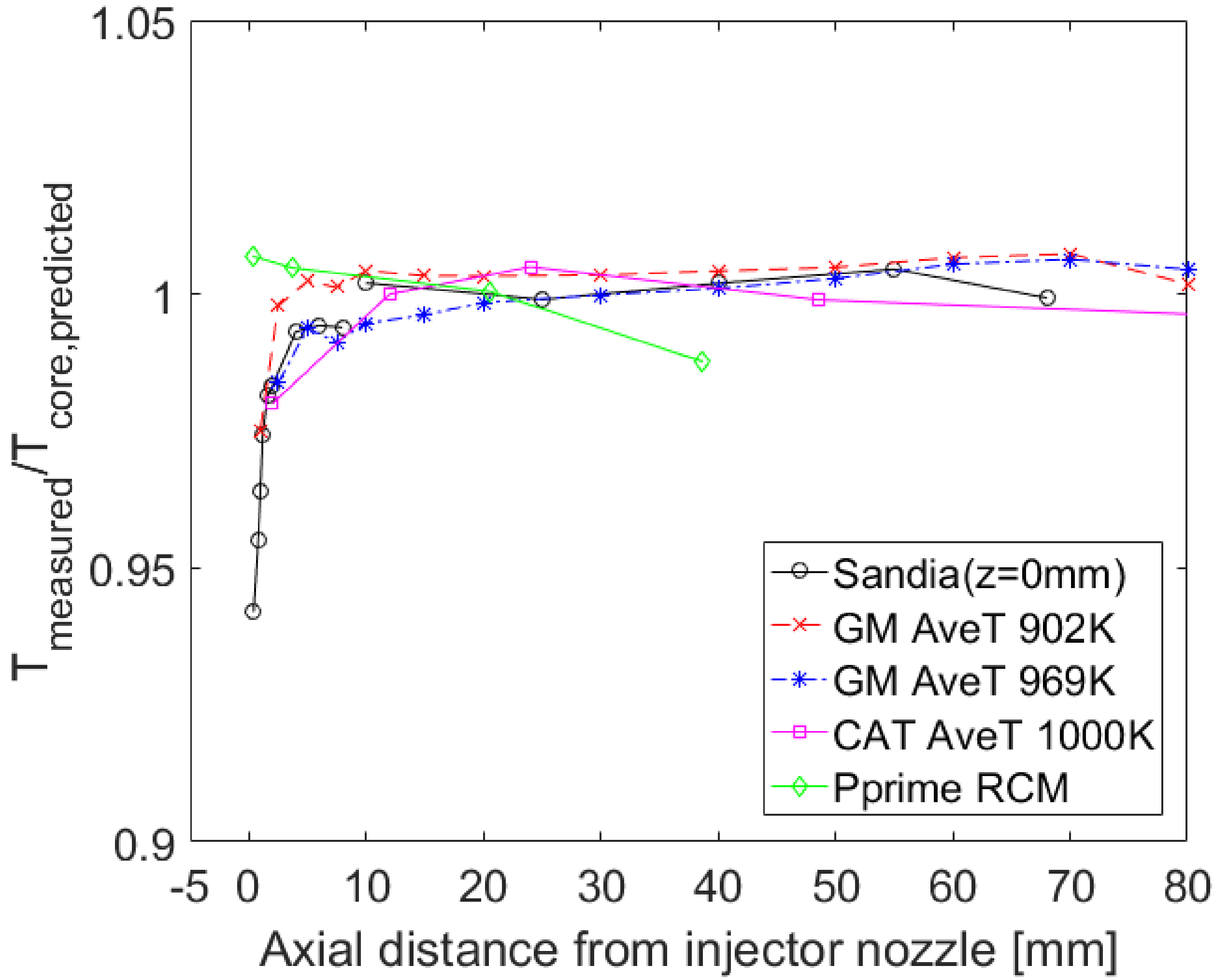
Temperature distribution is uniform on horizontal, except near the cold injector





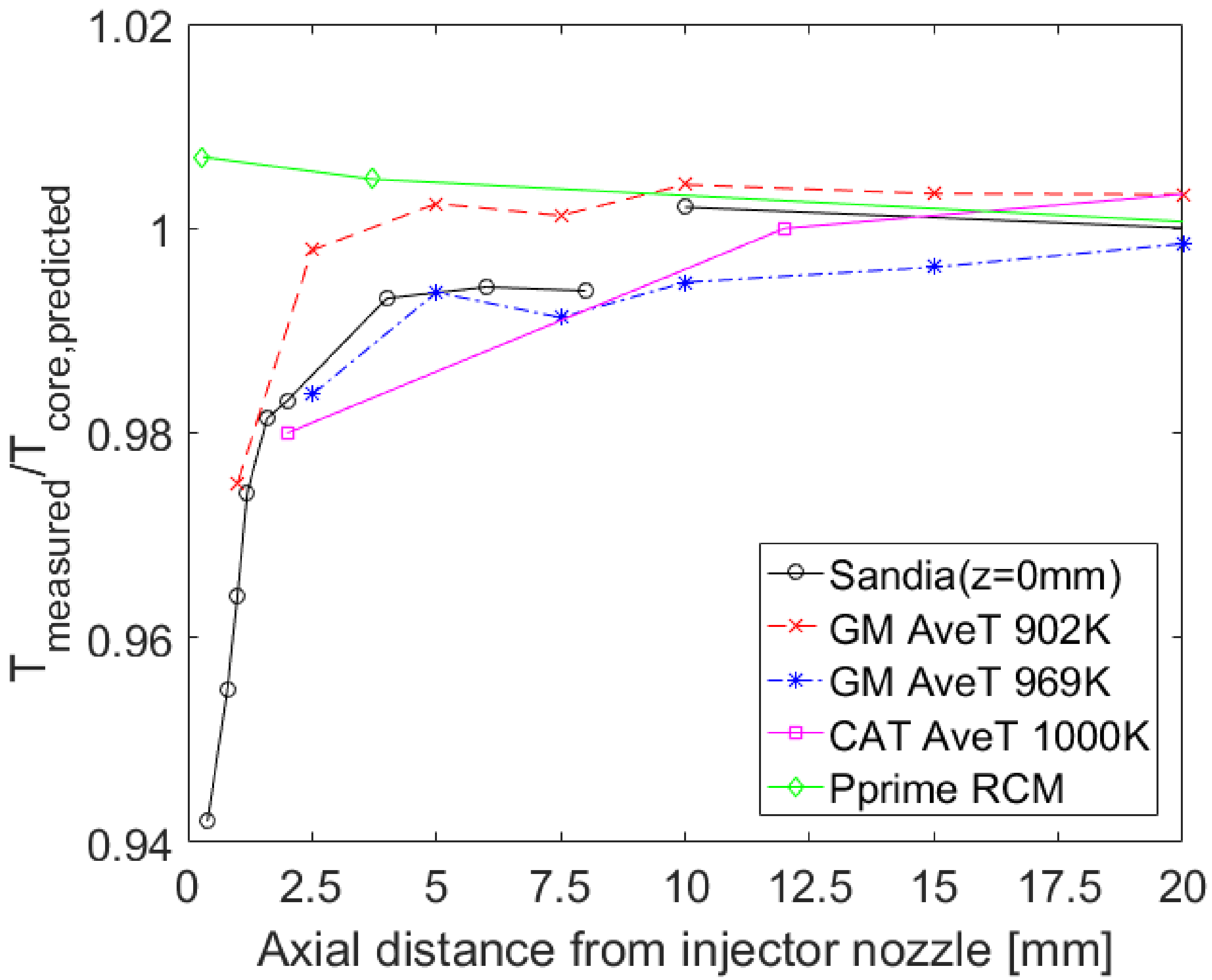
- At < 10 mm from injector, T decreases
- But lift-off length is only 16 mm

Temperature distribution from different facilities



- Temperature drop at the thermal boundary is less effect at the GM and CAT case, but we doubt the accuracy of collection.

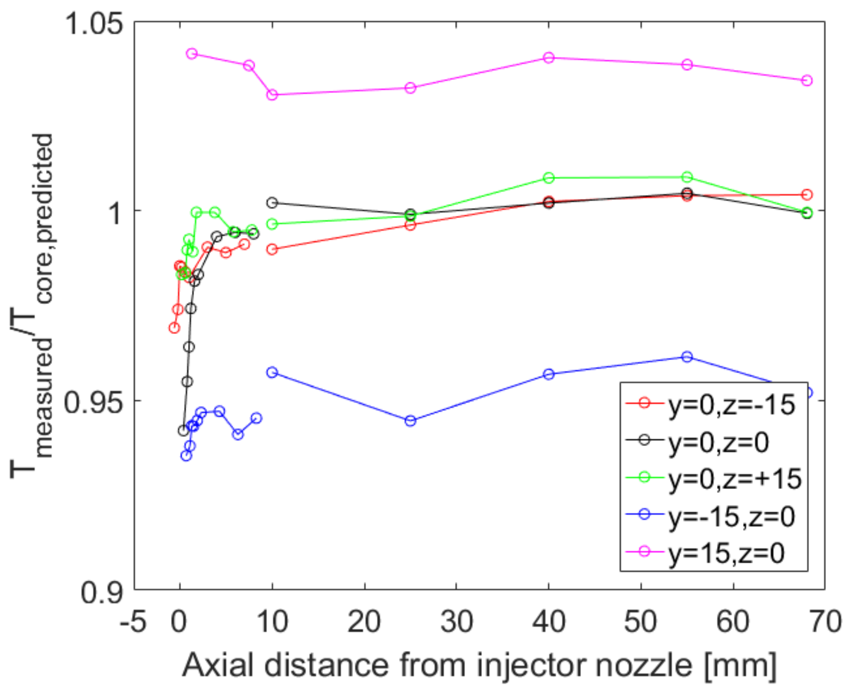
Temperature distribution from different facilities

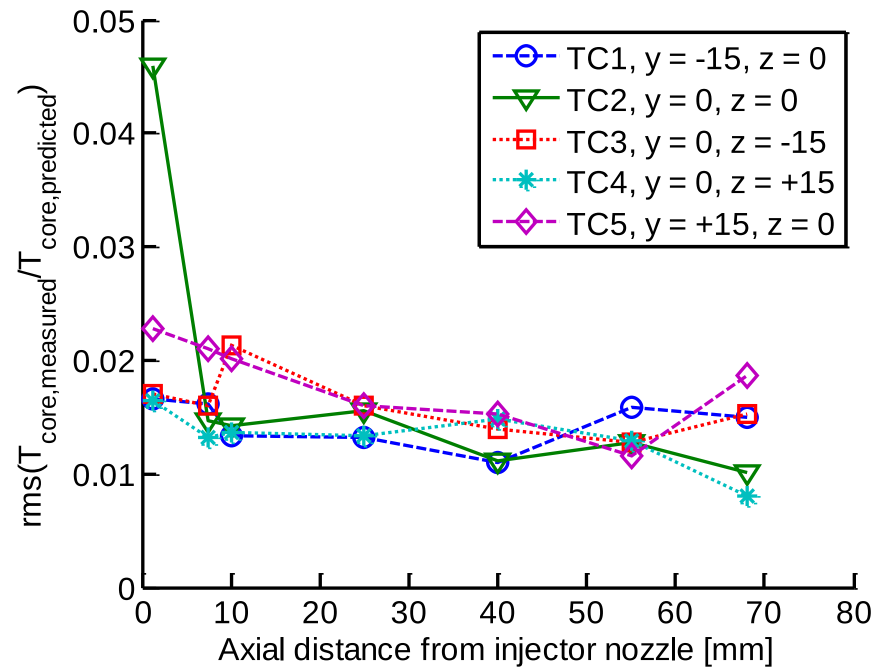


- Limitations of sheath TC measurements.
- Incorporate corrections.

Temperature fluctuations

Spray A temperature distribution



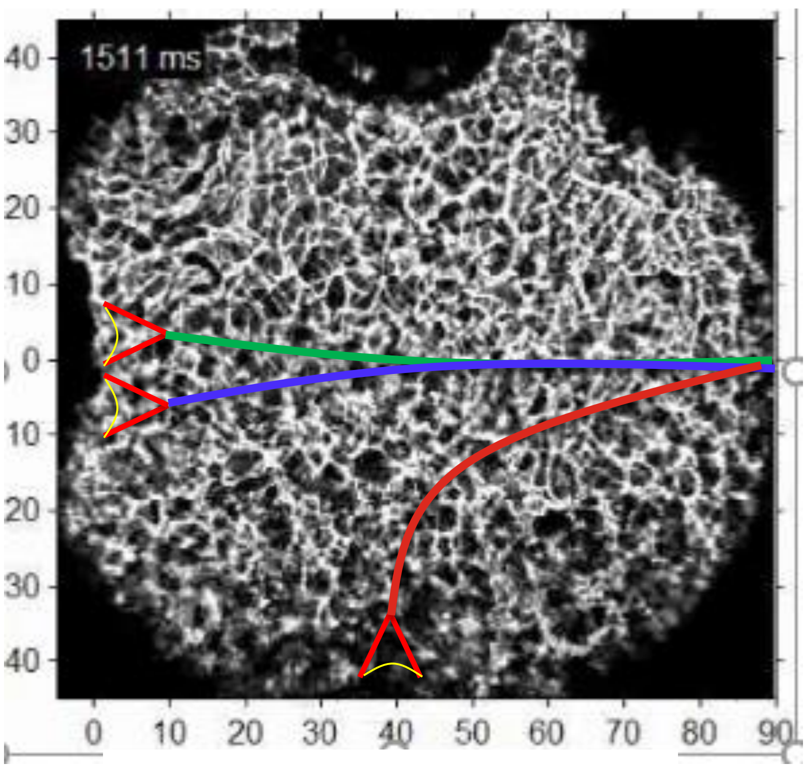


- Sandia vessel observe the highest variance only in thermal boundary layer

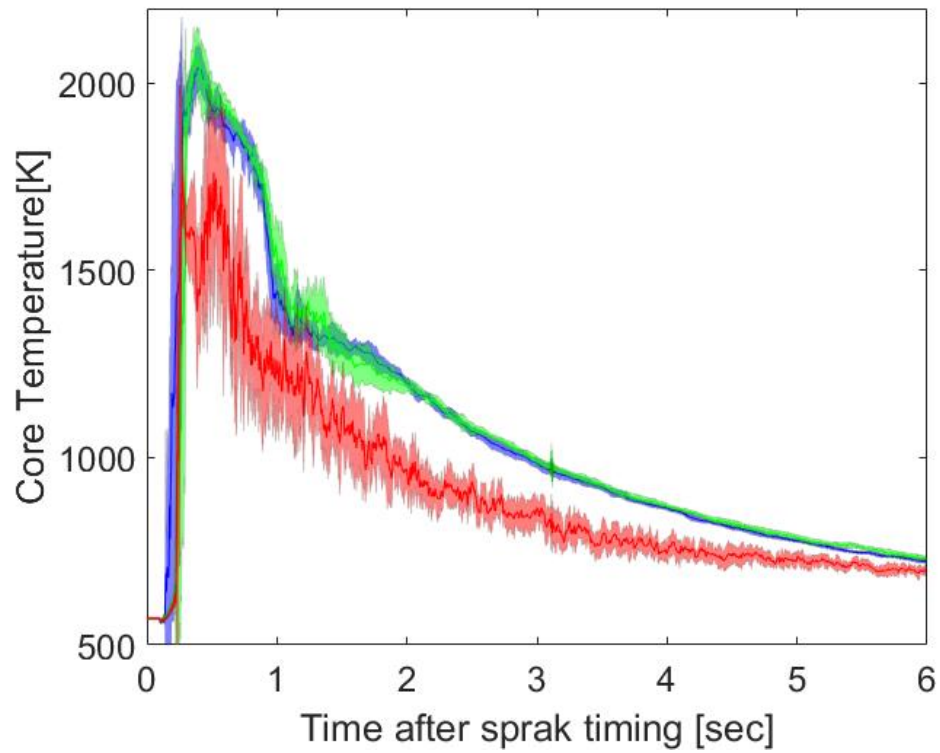
Temperature distribution near the wall

- The red is set at 0.8mm from laser entrance window—much lower than the measurements in the core, and much higher frequency. Suggests that if the injector were flush mounted, the temperature would be much less uniform.

Sandia injector protrudes 13mm from the flat wall



Laser entrance window



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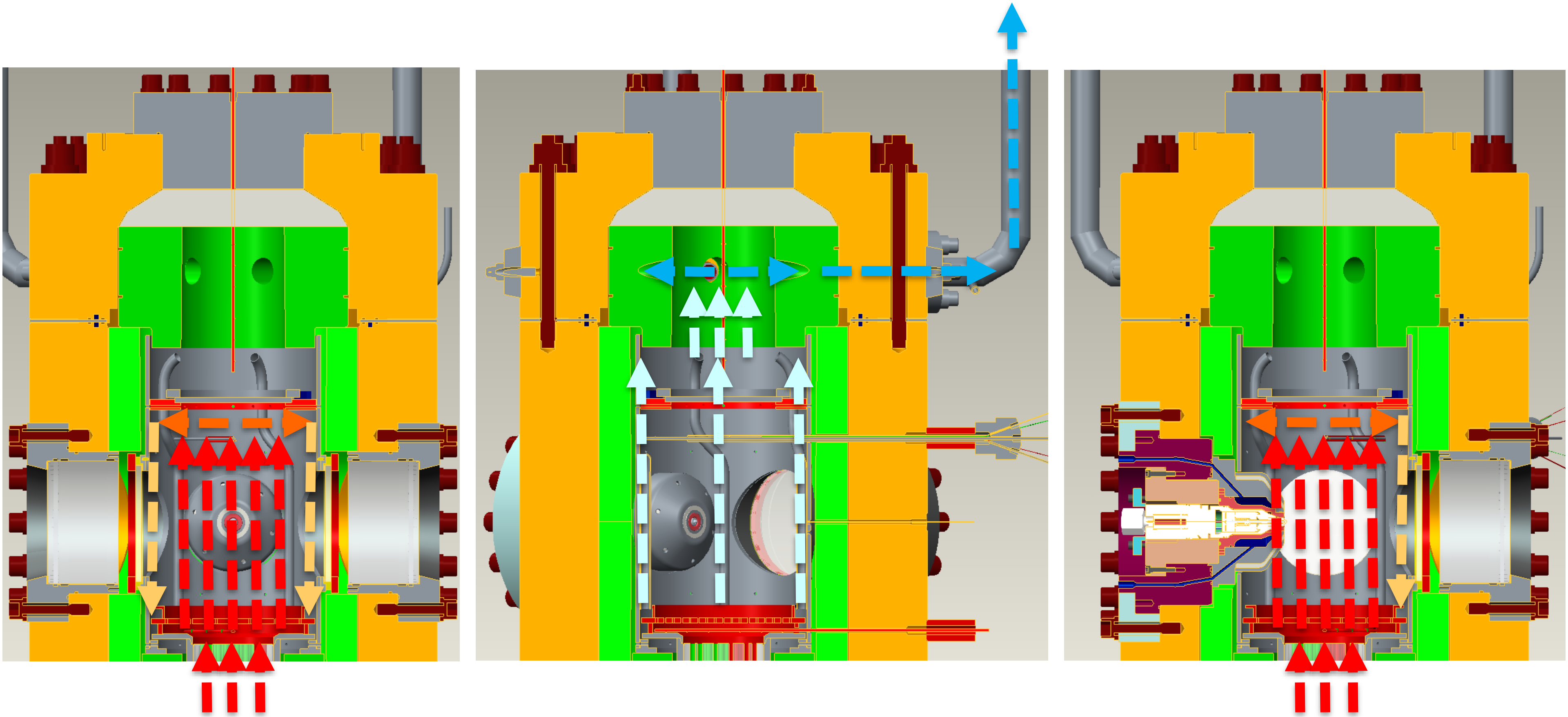
Buoyant Flow Path for Caterpillar Constant Pressure Vessel



What are the actual temperature and velocity distributions?

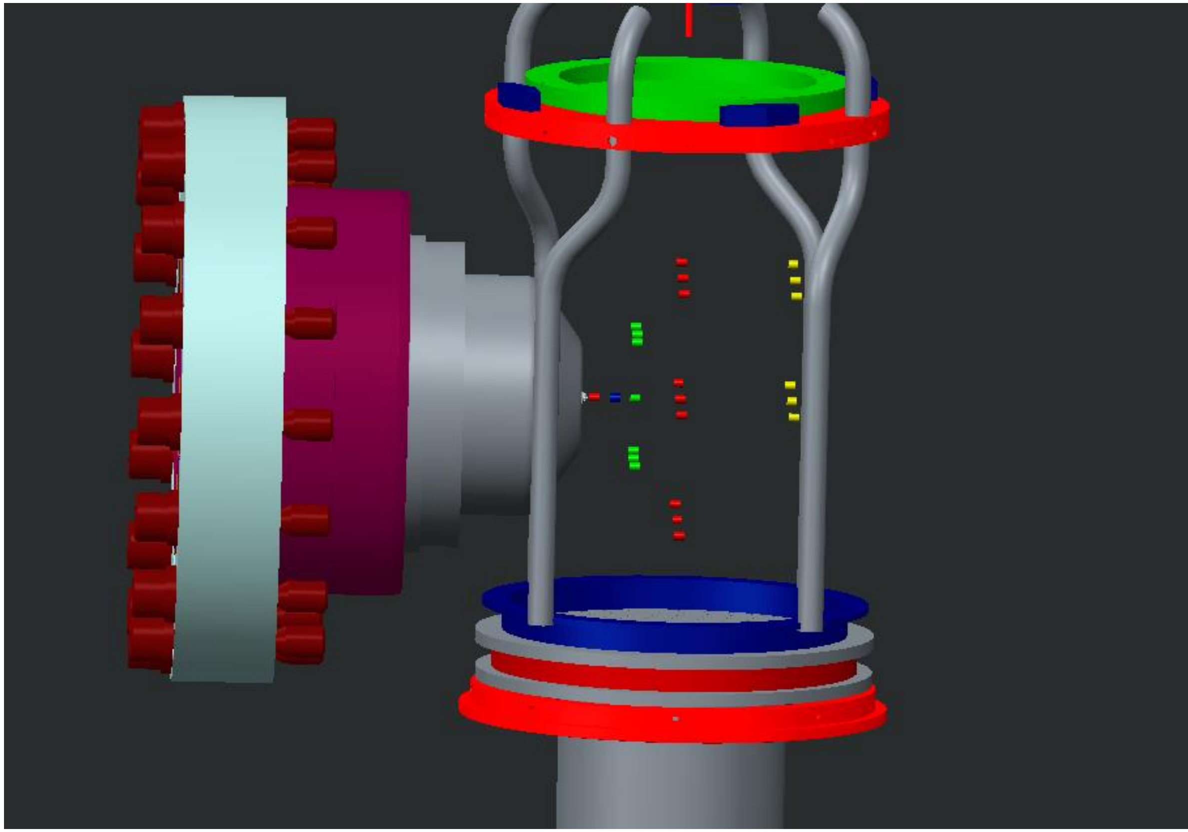
Thermocouple Orientation for Temperature Characterization

Array of 24 thermocouples arranged to characterize vessel temperature:

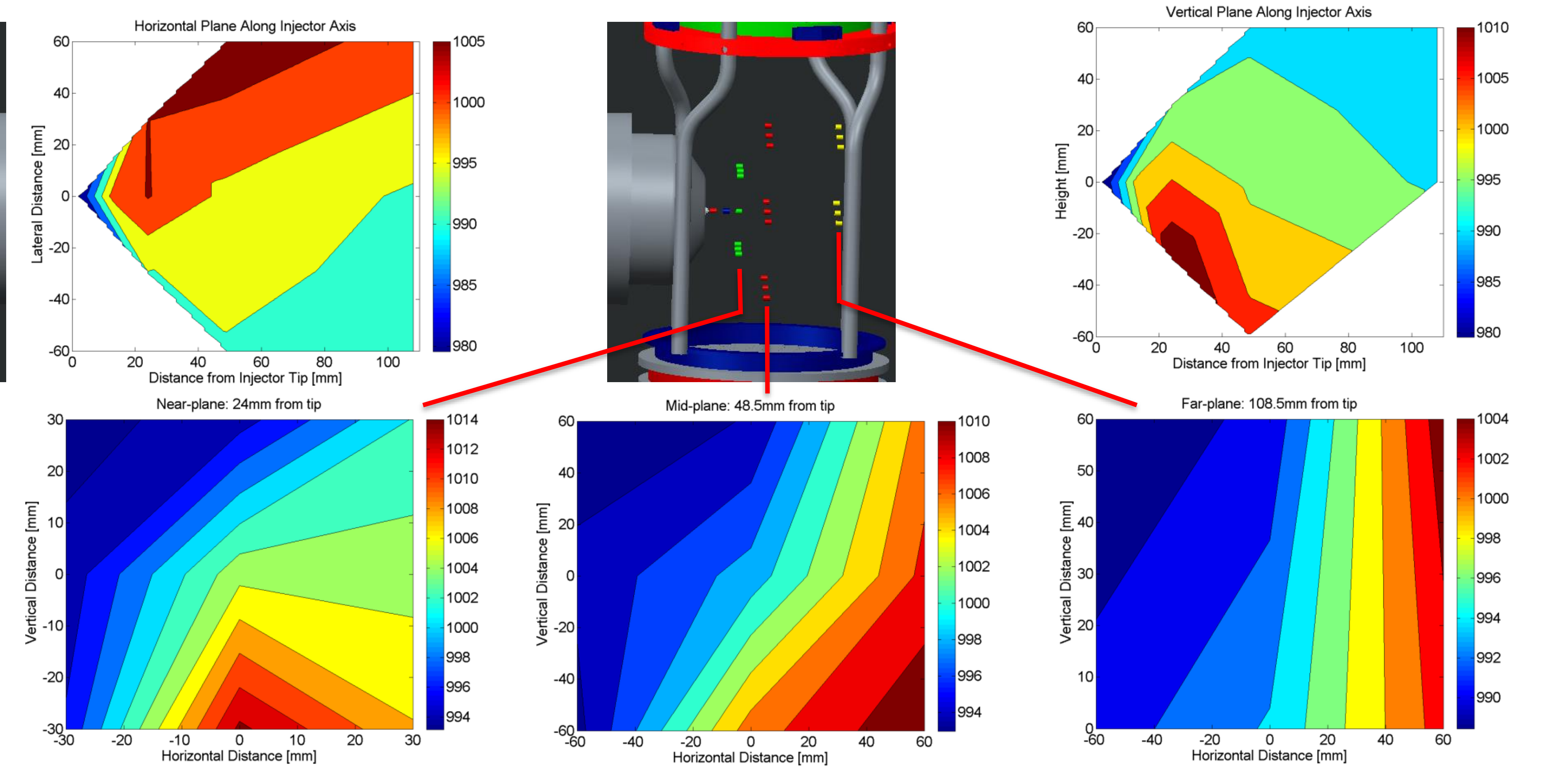
- K-type
- 1mm sheath
- Threaded through port opposite injector holder

Measurements in multiple planes:

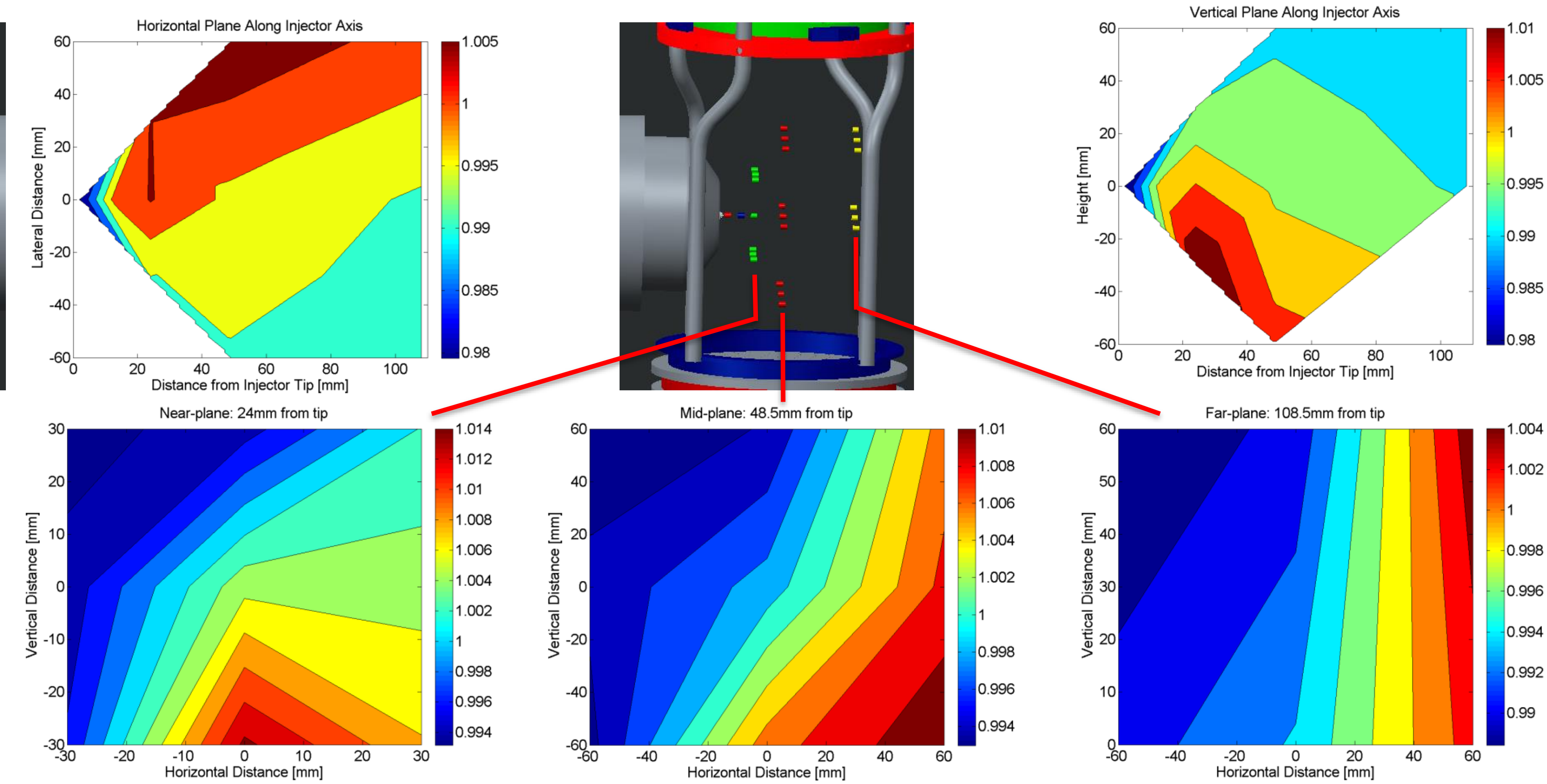
- Three vertical planes at varying axial distances
- Vertical and horizontal planes containing injector axis



Temperature Distribution in Caterpillar Constant Pressure Vessel



Temperature Distribution in Caterpillar Constant Pressure Vessel



Velocity Measurements in Caterpillar Constant Pressure Spray Vessel

Objectives:

Measure mean velocity flowfields

Quantify spatially varying turbulent fluctuations and length scales

Approach:

8Hz LaVision PIV system.

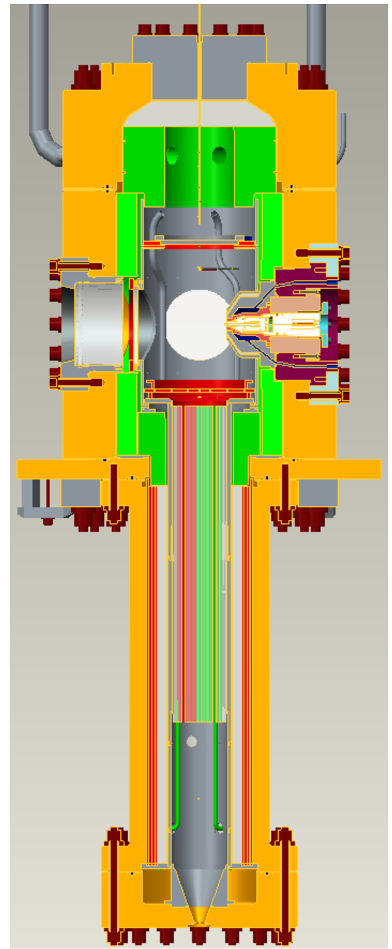
Seed flow with Superfine ZrO_2 Powder (500nm)

- Density controlled by downstream orifice and supply pressure
- Timing optimized to minimize flow disturbance and maximize signal

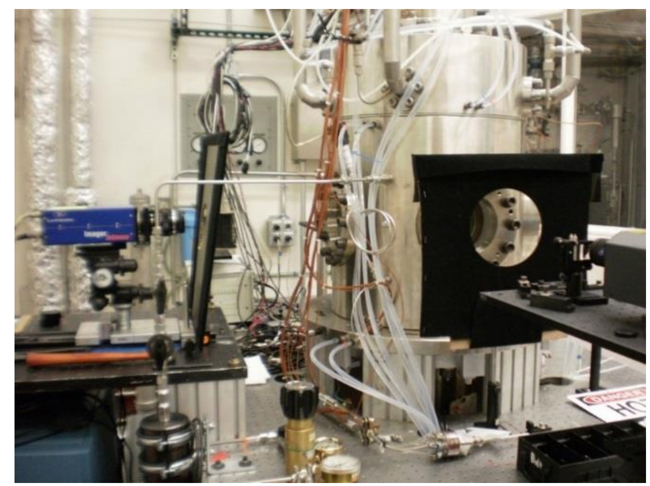
Acquire planar images at several distances from injector tip location

200 shots / image pairs acquired for flow field convergence.

Several magnifications and fields of view used to verify turbulent intensity and length scales.

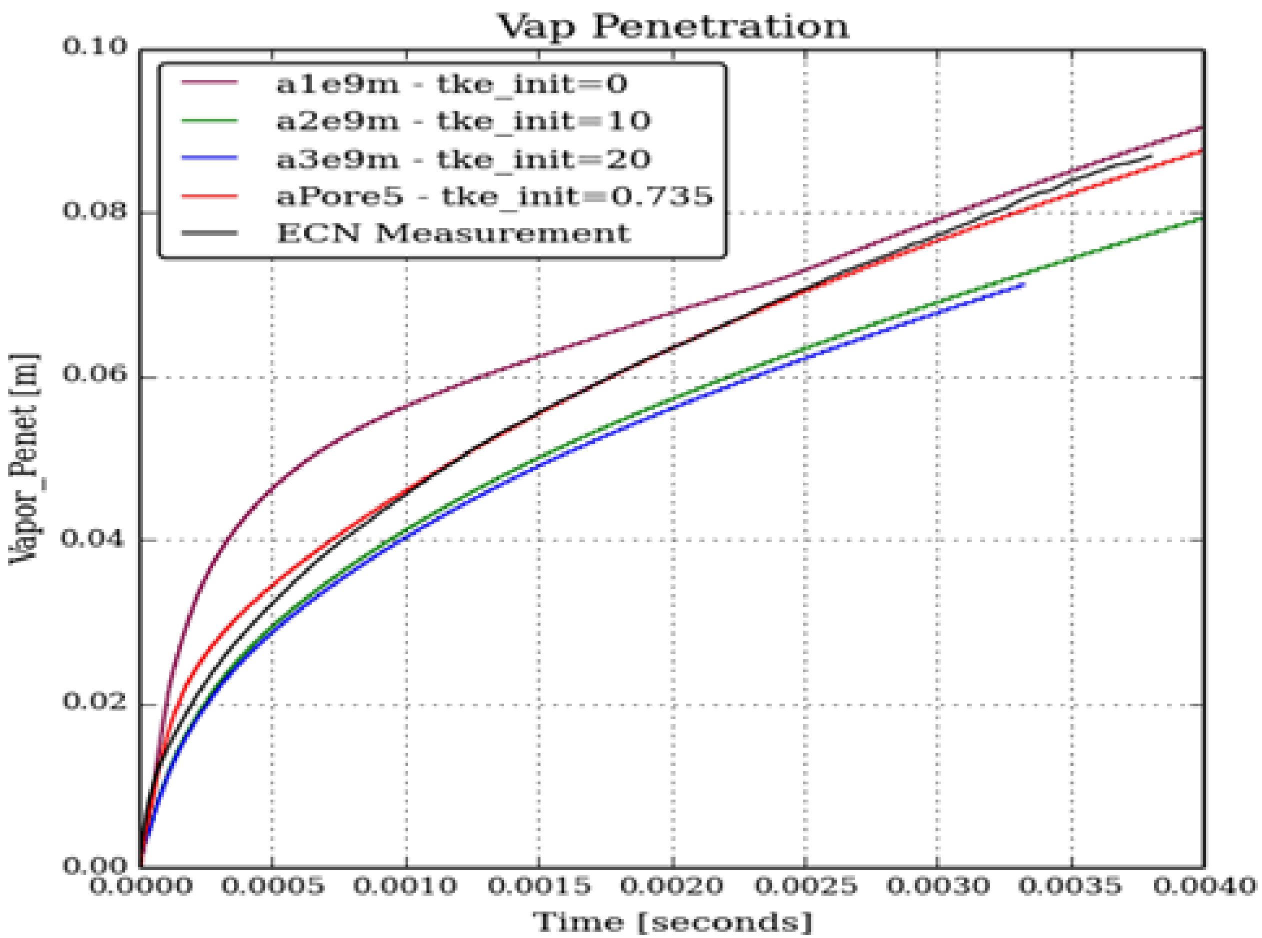


Test Conditions	
P_{HTPV} [bar]	60, 120
T_{HTPV} [K]	800, 900, 1000
Sheet Location [mm]	10, 18, 24, 49, 75, 88
Lens [mm] (magnification)	50, 105, 200



Simulated Vapor Penetration is Sensitive to Assumed Initial Turbulence

- Model overpredicts penetration for zero initial TKE
- Model underpredicts jet penetration for high initial levels of TKE.

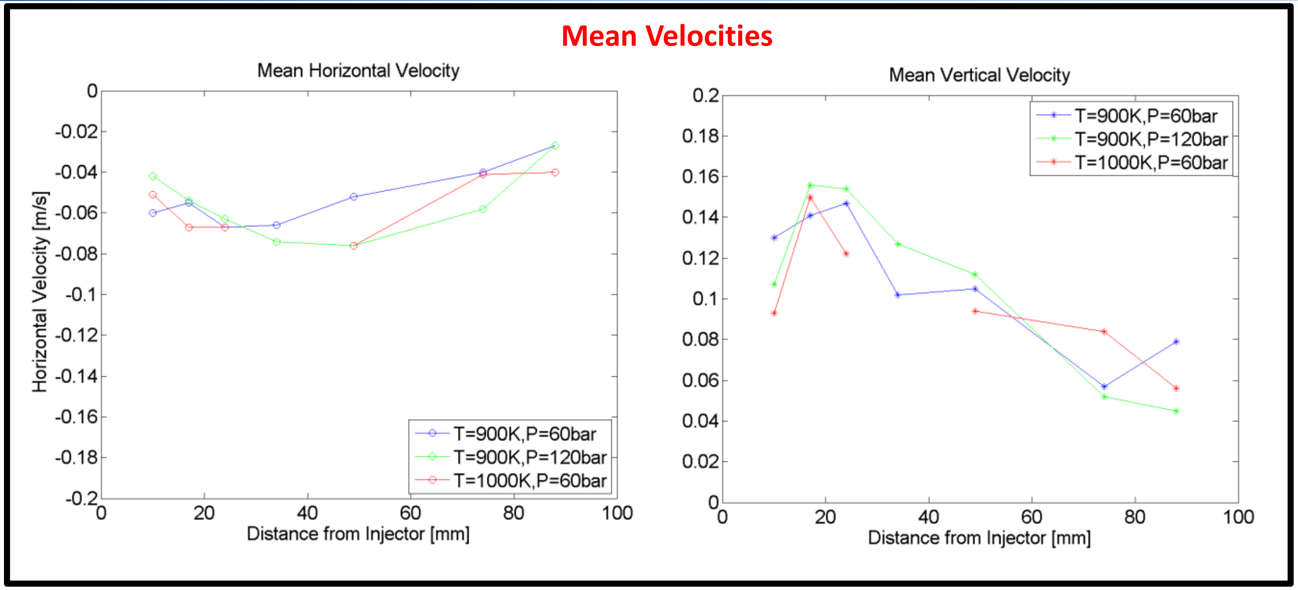


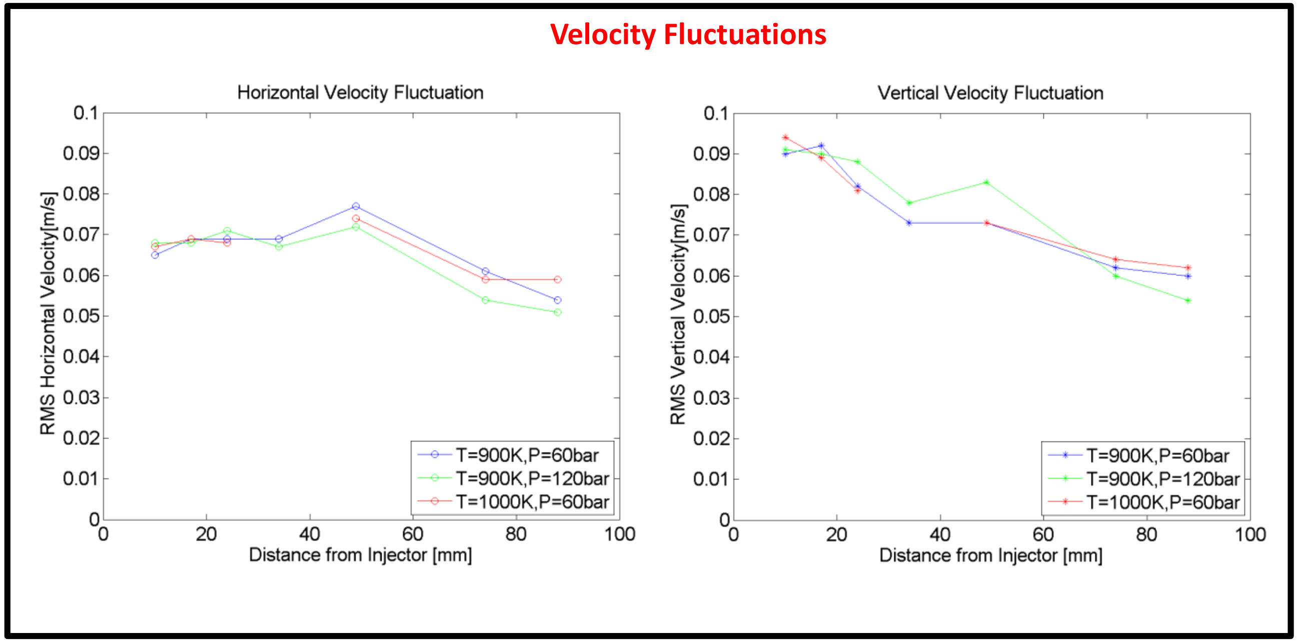
What initial turbulence parameters should be used for spray simulations?

What are the background turbulence levels in spray vessels and how do they vary?

Velocity Measurements Exhibit Consistent Trends Over Range of Conditions

- Modest effects of ambient temperature and pressure
- Low bulk horizontal fluid motion; local max near center
- Bulk vertical fluid motion same order as in/out flow; maximum near cold injector holder
- Isotropic turbulence near vessel centerline
- Vertical turbulent component increases quickly near injector holder





Mean Velocity and Turbulence Levels Reflect Differences in Spray Vessel Type

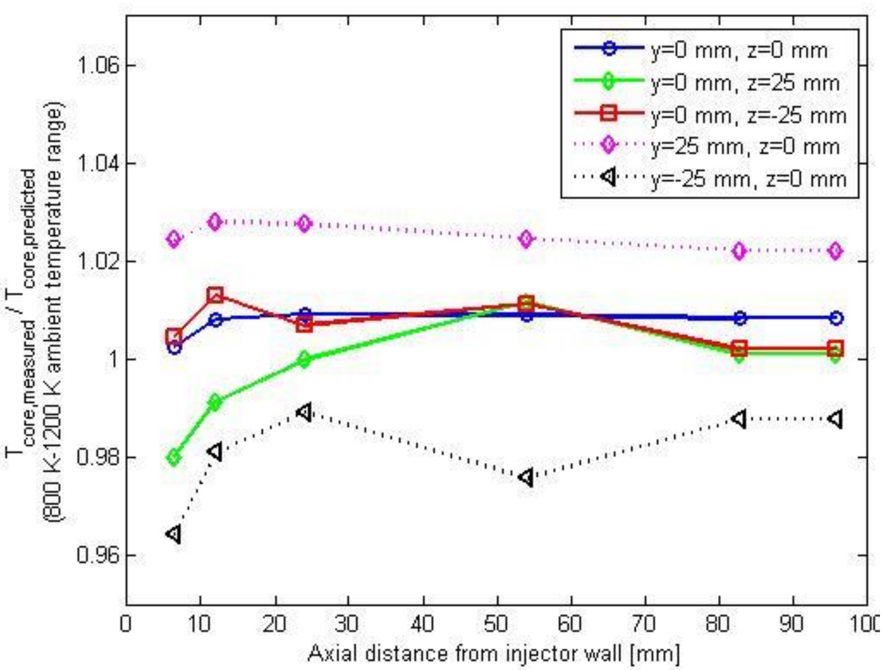
- Constant volume pre-burn vessel has lowest mean velocities
- Caterpillar constant mean velocities are higher; still represent very small displacement during injection
- TKE in both vessels is low; Caterpillar vessel turbulence is higher; simulations needed to determine computational significance
- Lingering questions:
  - Isotropy
  - Turbulent length scale

	Caterpillar Constant Pressure Vessel	Sandia Constant Volume Vessel (1000 rpm)
Mean Velocities:	*0.12m/s (.110/.055)	0.03m/s (.028/.008)
Velocity Fluctuations:	0.07m/s (.065 / .077)	0.018m/s (.017,.020)
Turbulent Kinetic Energy:	0.008m^2/s^2	0.0005 m^2/s^2
Turbulent Length Scale:	10-15mm	unknown

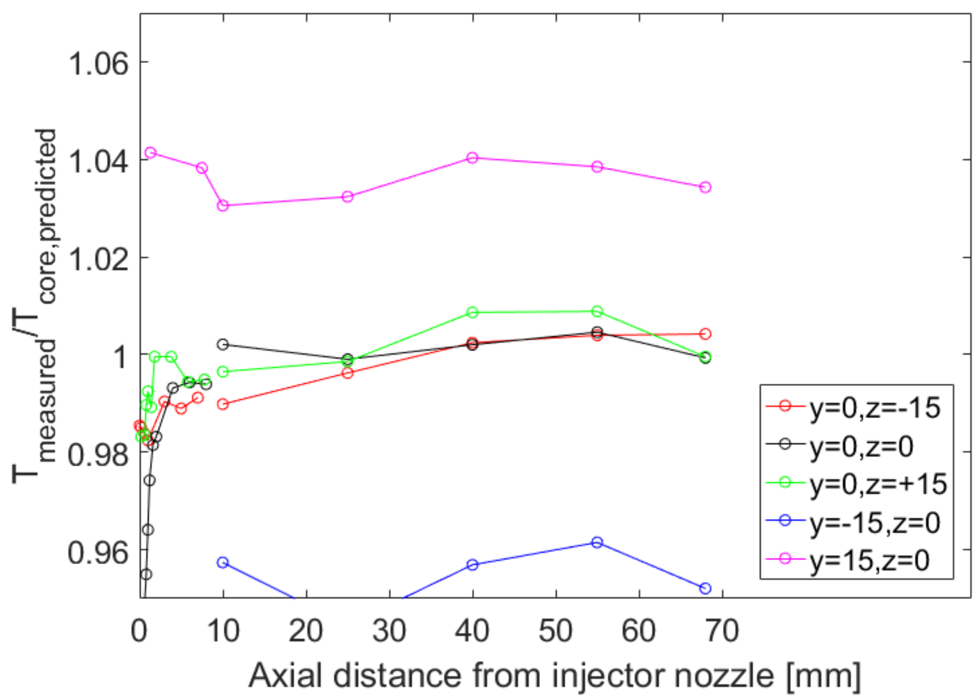
*Corresponds to 0.5mm displacement during 5ms injection

$$RMS = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(V_i - \bar{V})^2} \qquad \bar{V} = \frac{1}{N}\sum_{i=1}^{N} V_i \qquad TKE = \frac{1}{2}\left(RMS_x^2 + RMS_y^2 + \left(\frac{RMS_x + RMS_y}{2}\right)^2\right)$$

Velocity effect on temperature field?



Spray H conditions. 8000rpm 14.8kg/m3

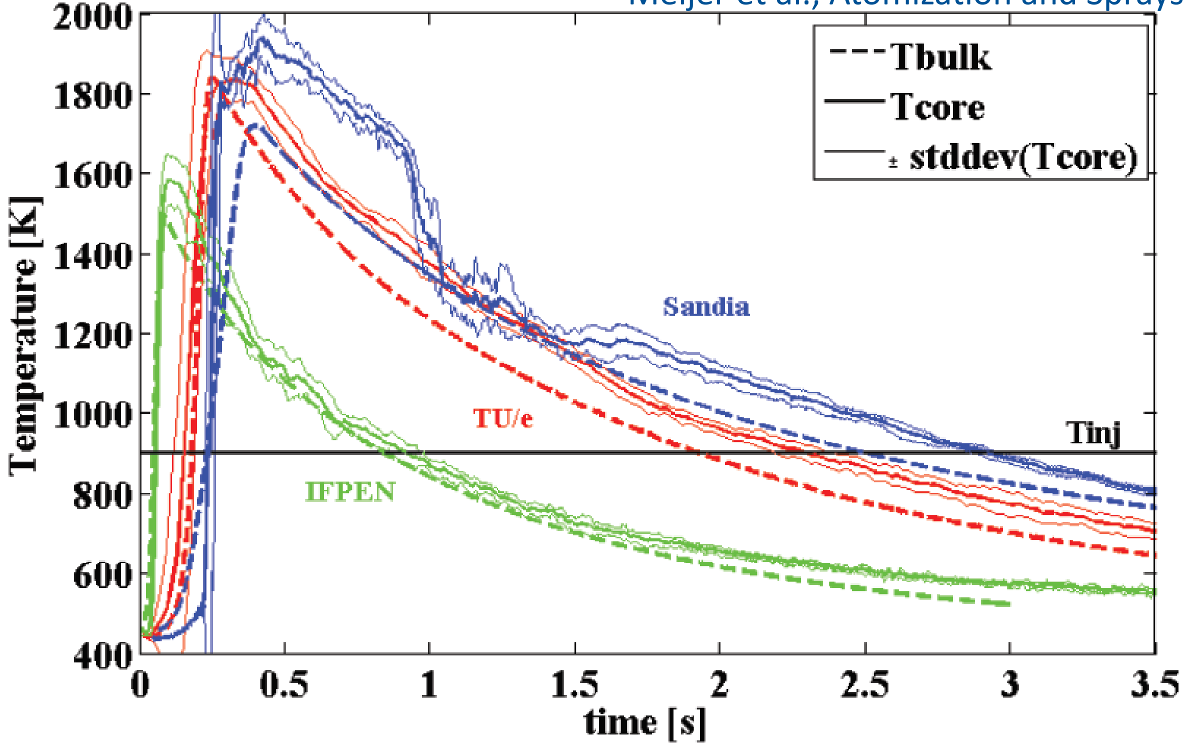


Spray A conditions. 1000rpm 22.8kg/m3

- Higher fan speed shows more uniform temperature fields

Velocity effect to the pre-burn

Meijer et al., Atomization and Sprays 22(9):777-806 (2012)

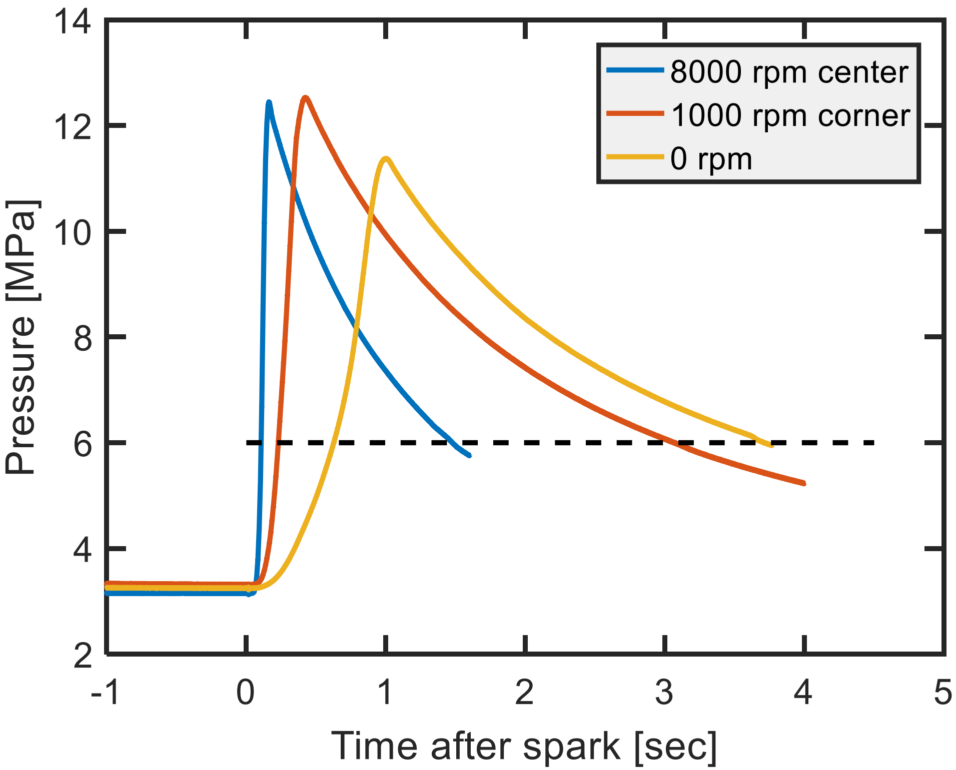


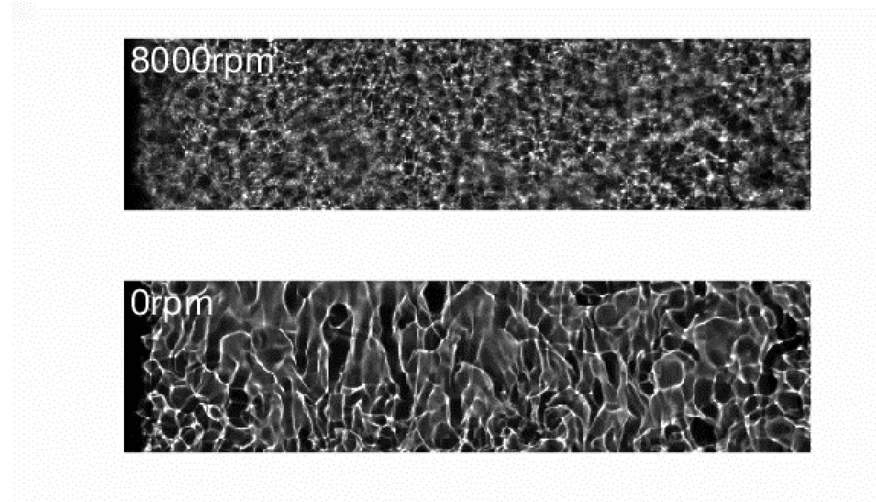
	IFPen	Sandia	TU/e
Fan speed (rpm)	3140	1000	1890
Lift-off length (mm)	15.4	16.5	15.8
Ignition delay (µs)	400	440	410

- Faster cooldown DOES correspond to higher velocity and turbulence

(Similar surface area to volume ratio in these chambers)

Velocity effect to the pre-burn



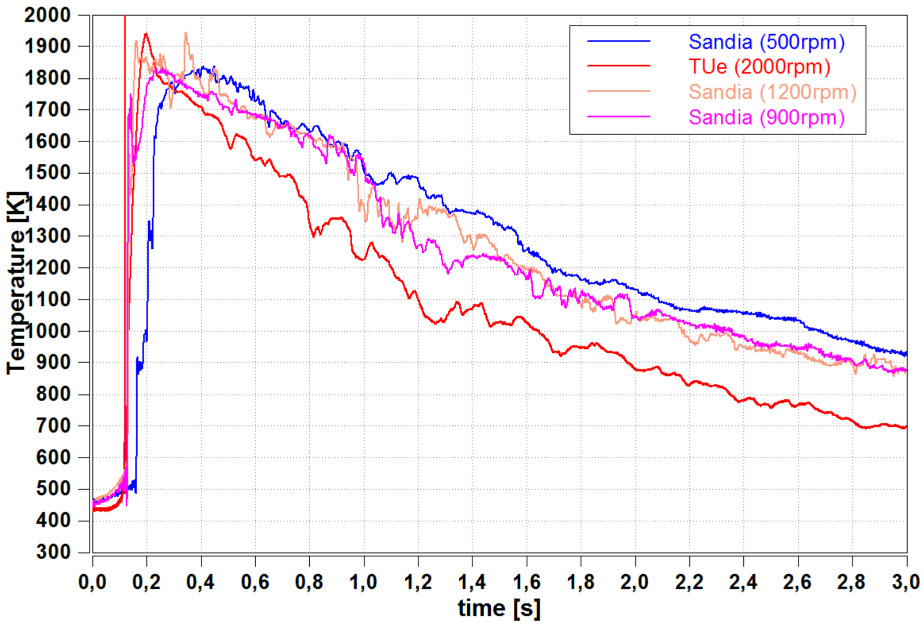


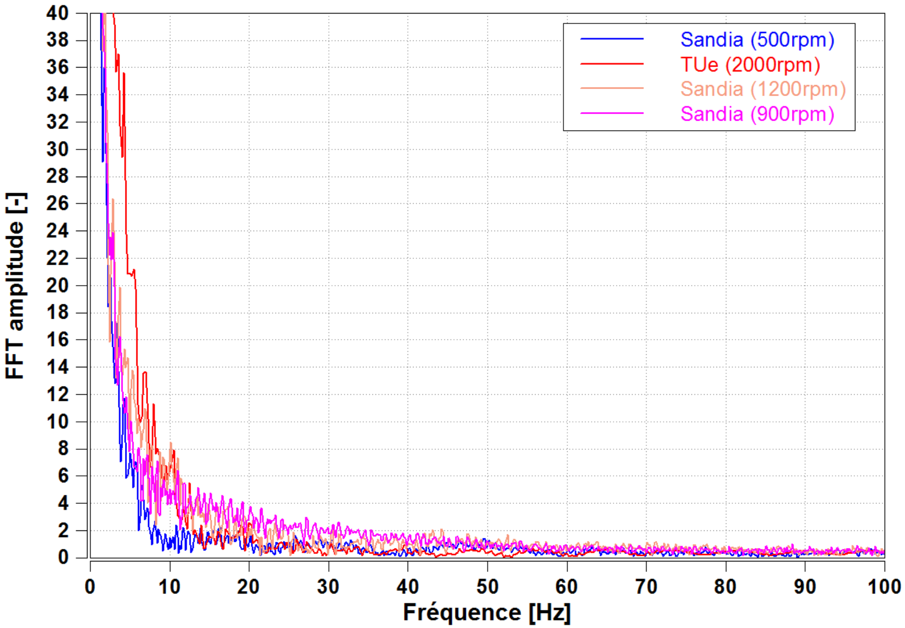
Spray A conditions (22.8 kg/m3)

- Fan speed affect to Initial turbulent kinetic energy.
- What is the effect of TKE to spray?

Velocity effect to the pre-burn in same facility

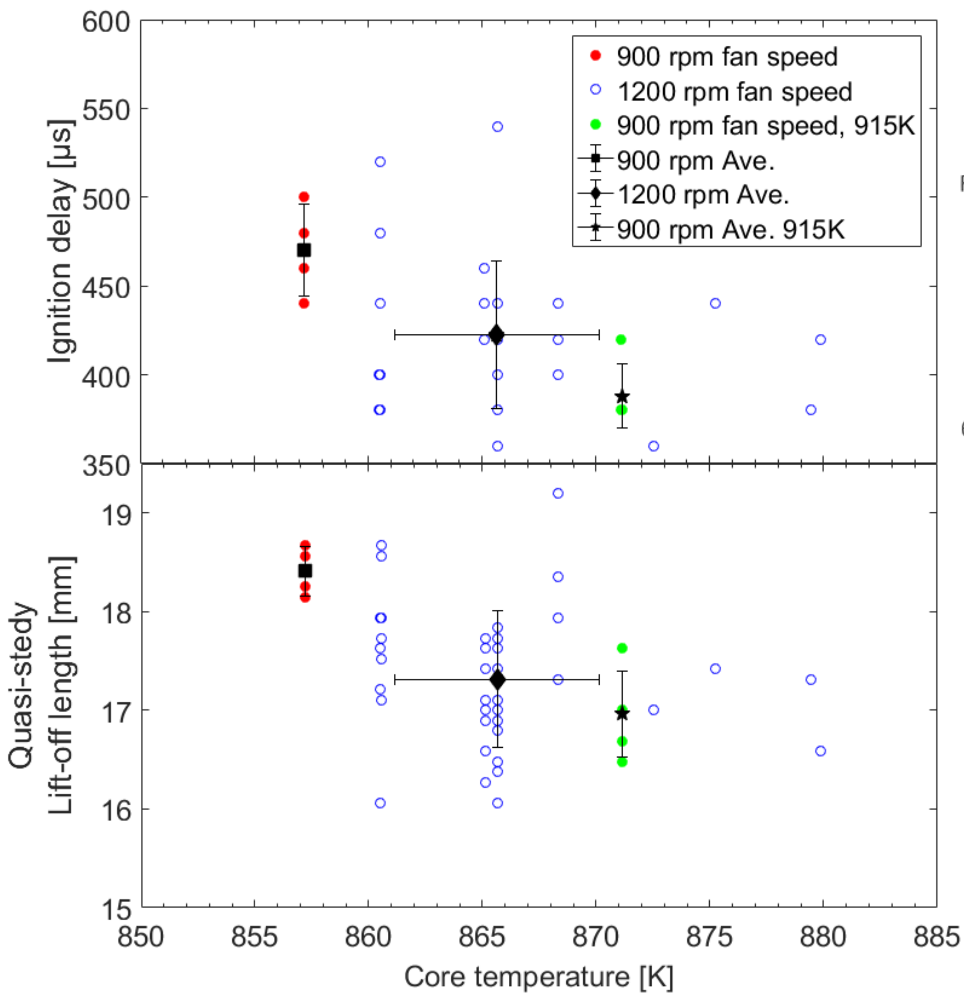
Comparison of cool down Sandia (500,900,1200 rpm) , TUe (2000 rpm)

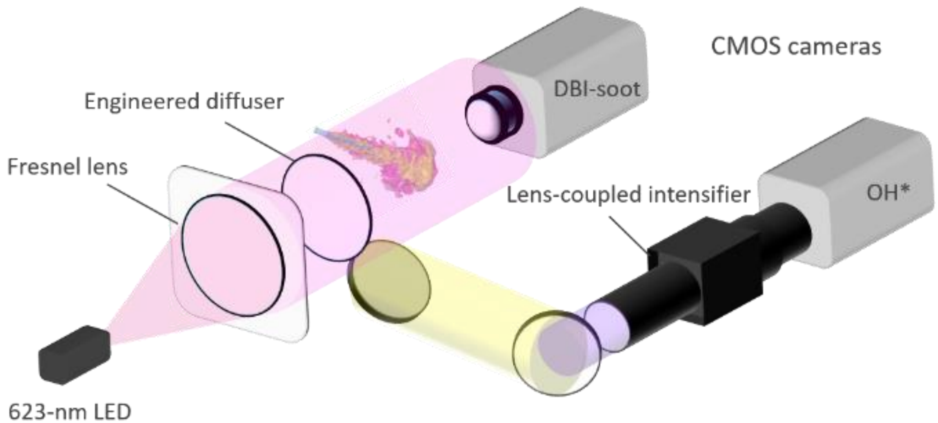


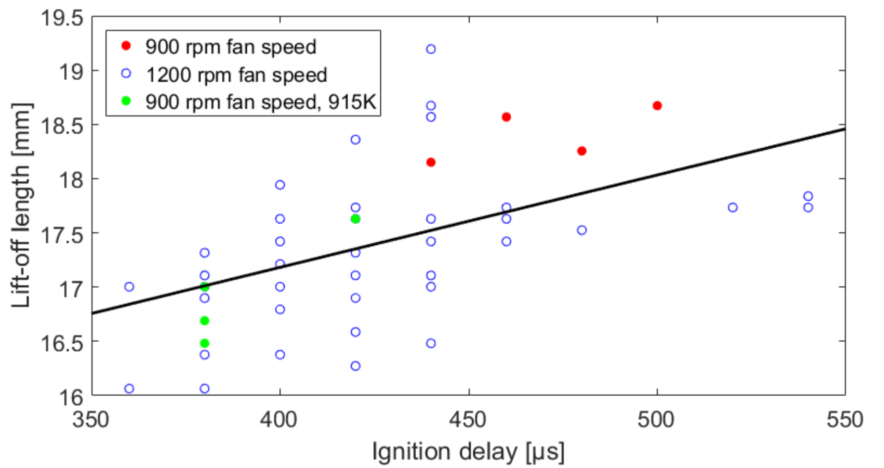


- Higher Fan speed => higher amplitude fluctuation at low frequencies

Velocity effect to the Spray (Spray A fan speed sweep)

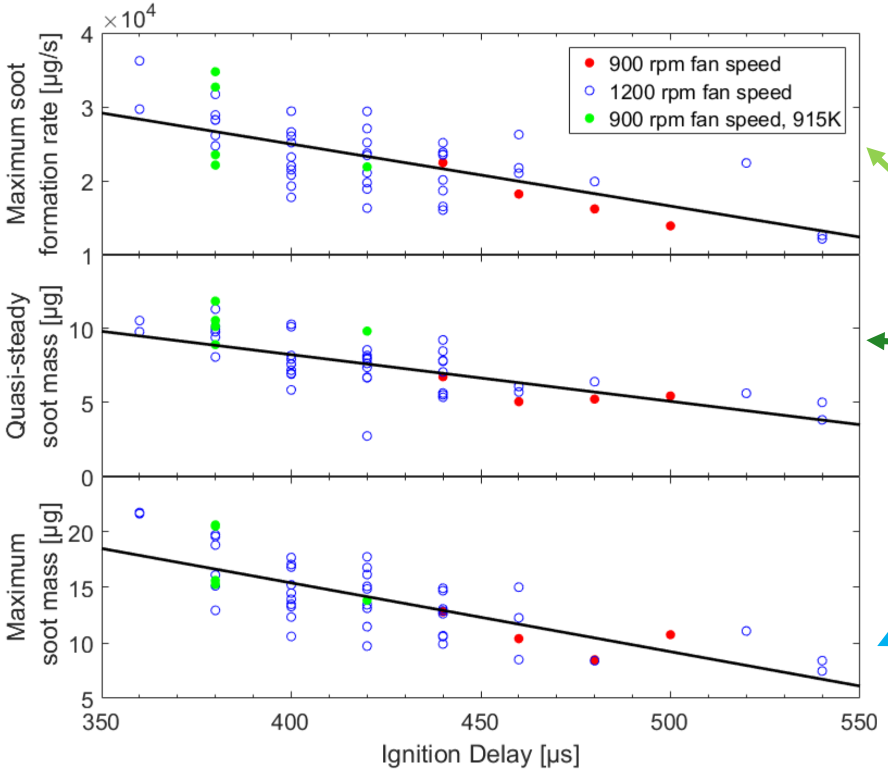


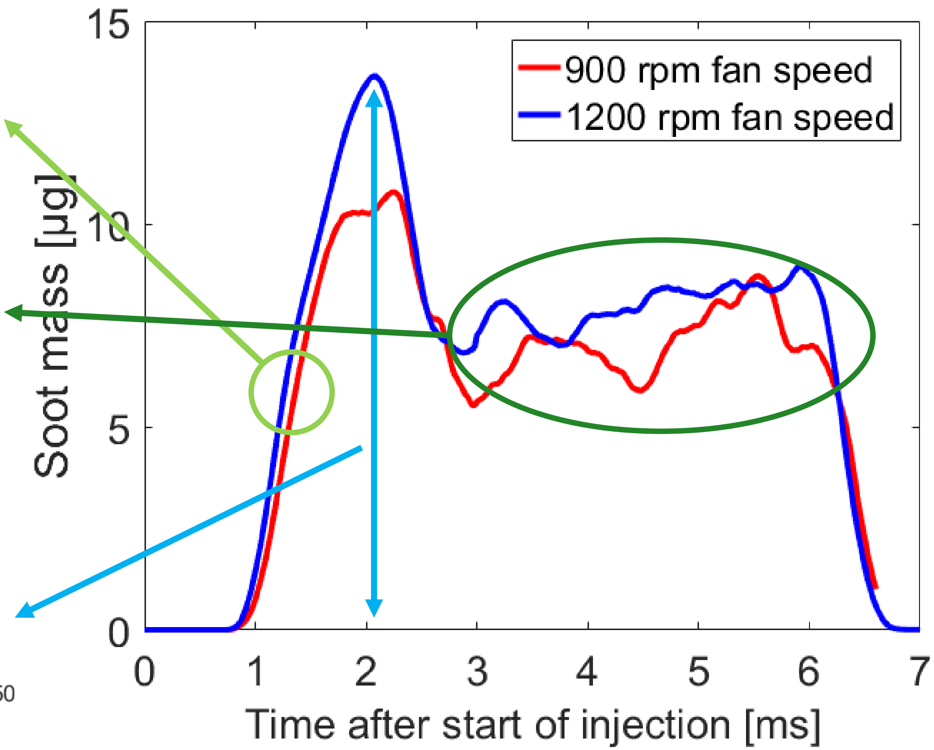




- Ignition delay and LOL are described by temperature, not the “Fan speed”

Velocity effect to the Soot (Spray A fan speed sweep)





- ➢ Temperature field pocket -> Ignition delay and Lift-off length -> Soot
- ➢ Spray characteristics do not change

Conclusion and Suggestions

- Near the injector window, temperature drop is significant especially for constant volume chamber.

- Constant pressure chamber showed slightly high TKE about 0.008 than constant volume vessel about 0.0005m/s

SUGGESTIONS for modeler

- Please use the non-uniform temperature distribution!!

(We are not ready to propose the “one” temperature distribution which can explain the whole facility)

- To apply the TKE to simulation is also important to get “actual temperature” fields.

Acknowledgements

- Thanks Panos Sphicas (IC), Scott Skeen (Sandia), Scott Parrish (GM), Noud Maes (Tue), Michele Bardi (IFPEN), Ob Niphalai (Prisme), Tiexua (CMT) and Russ Fitzgerald (Caterpillar) for providing the temperature and velocity data of the vessel.

- Thanks Lyle Pickett, Gilles Bruneaux and Raul Payri for encouraging for this topic session.

Backup Slides

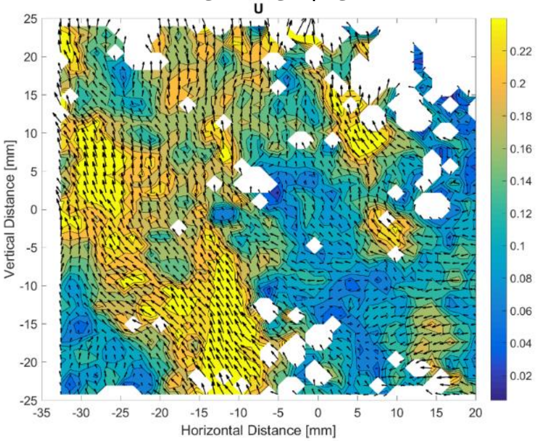
Vertical Plane: 24mm from Injector Tip

Pa = 60bar, Ta = 900K

Δt = 800μs, 50mm lens

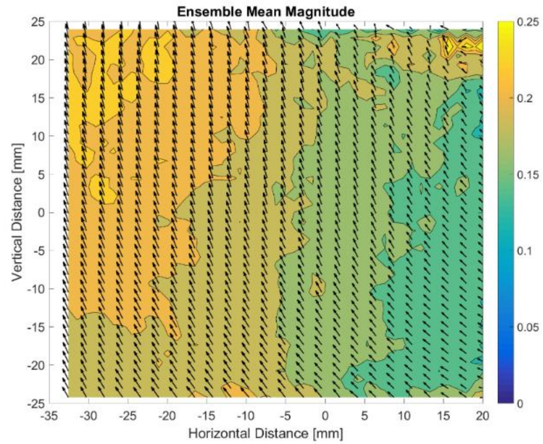
Instantaneous Velocity

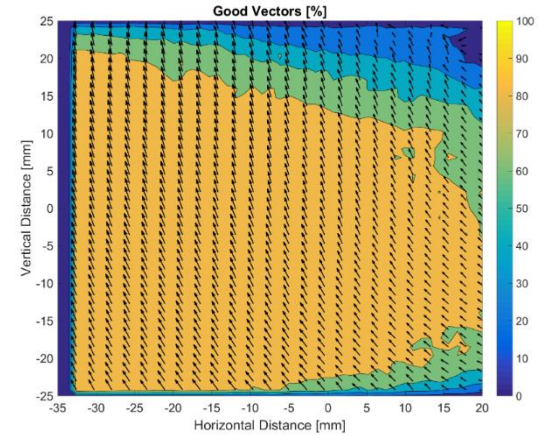
$\boldsymbol{U} =_{\text{u}} \overline{\boldsymbol{U}} + \boldsymbol{U}'$



Mean Velocity

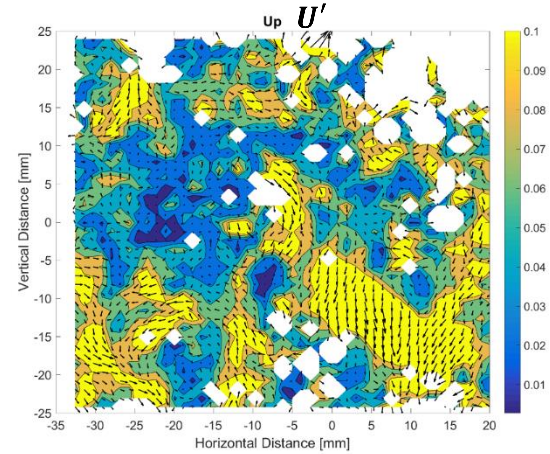
$\overline{\boldsymbol{U}}$





Velocity Fluctuations

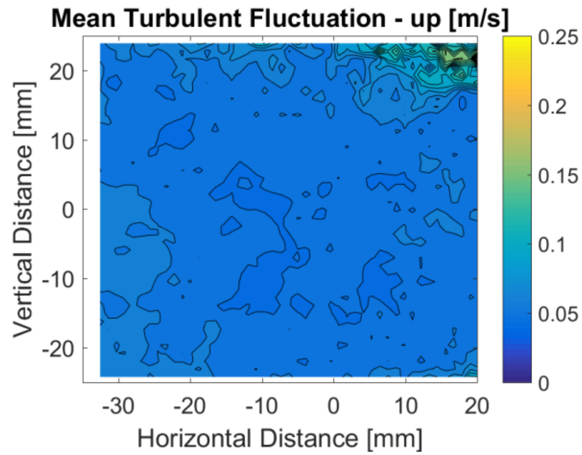
Up $\boldsymbol{U}'$

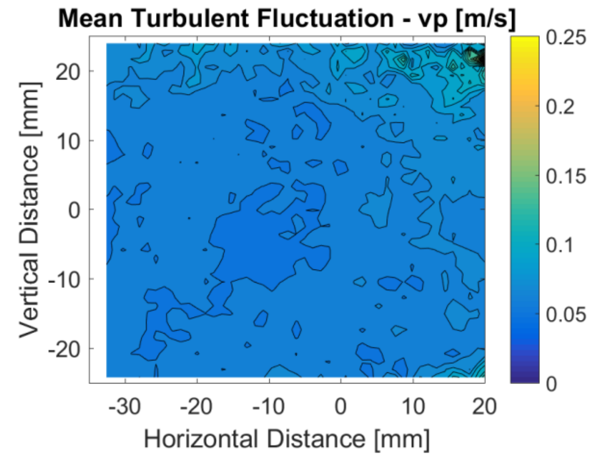


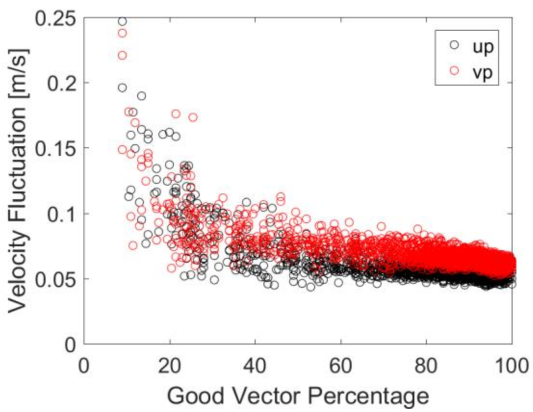
Spatially and Temporally Resolved Turbulence Statistics

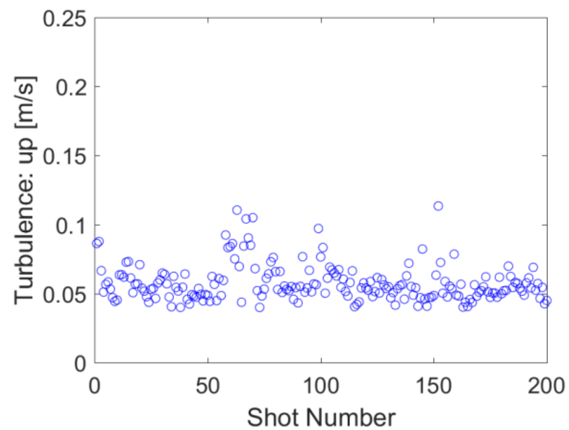
<u>Characteristics of HTPV Turbulence</u>

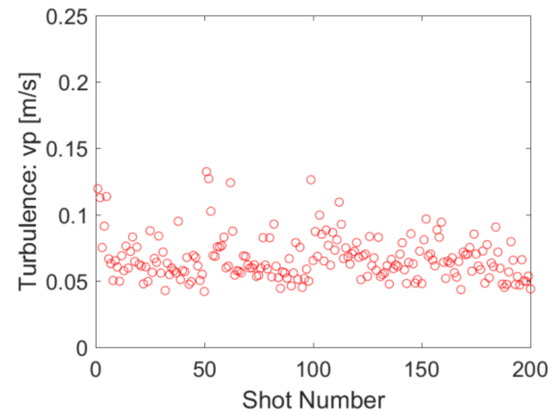
- Seeder adds some turbulence; need to careful analyze data ‘after settling’
- Turbulence appears to be homogeneous and isotropic
- ‘Good vectors’ crucial for good turbulence statistics.
- Turbulence intensity is on the order of 25-30%











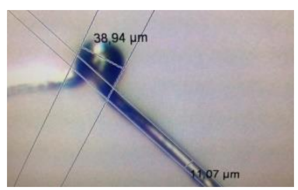
Review of error correction / response compensation

	Tck7	Tc	Tg7_Nu	Tg7_Nu_min	Tg7_Nu_max		
effect of velocity			Vmeasured	0,05	1	m/s	
	930	936	936	939	934		
				9	4		

	Tck12	Tc	Tg12_Nu	Tg12_Nu_min	Tg12_Nu_max	
effect of velocity			Vmeasured	2	3	m/s
	830	873	869	872	866	
				42	36	

dTj/dt = ~ 17k/ms

TU/e, type R
d_w = 50 µm
d_j = 100 µm
Correction (SOI) = ~ 23 K



Prisme (Orleans, France), type K
d_w = 13 µm
d_j = 39 µm
Correction (SOI) = ~ -21 to 28 K

Pprime (Poitiers, France), type K
d_w = 7.6 µm
d_j = ~ 8 to 14 µm
Correction (SOI) = ~ -1 to 8 K

Review of temperature measurement in ECN facilities

Comparison of data from literature

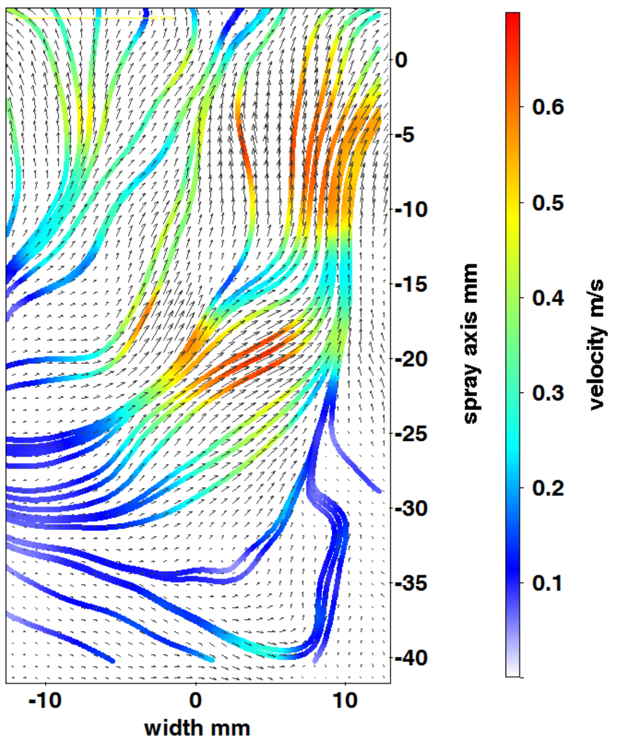
Institution	Facility	Thermocouple type	Wires dimension	Error corrections $T_g = T_j + conduction\ error + \tau\frac{dT_j}{dt} + \frac{\varepsilon\sigma}{h}(T_j^4 - T_w^4)$ $\tau = \frac{\rho_t C_t d_t}{4h}$				
				Hypothesis	Conduction	convection	Radiation	total correction
Sandia SNL	CVP	Type-R : Pt/Pt+13Rh	50 µm	Conduction error neglected	$l > \sqrt{\alpha\tau}$ no correction	yes	yes	4 to 10 K (around 900 K)
TU/e	CVP	Type-R : Pt/Pt+13Rh	50 µm	Conduction error neglected	no correction	yes	yes	4 to 10 K (around 900 K)
IFPEN	CVP	Type-K : Ni/Cr	single 50 µm or 25 µm?	Conduction error neglected	no correction	yes	yes	4 to 10 K (around 900 K)
Caterpillar	CPF	Type-K : Ni/Cr	1 and 3 mm	* Temperature is homogeneous in the small volume where the different thermocouples with different diameters are placed * Temperature is averaged over 10 s	no correction	no correction (temperature averaged over time)	$T_g = T_j + \frac{\sigma\varepsilon v^{0,45} d^{0,55}}{0,56kU^{0,45}}\left(T_j^4 - T_s^4\right) + T_j$	?
CMT	CPF	Type-K : Ni/Cr	?	* Temperature is homogeneous in the small volume where the different thermocouples with different diameters are placed * Temperature is averaged over 20 s	no correction	no correction (temperature averaged over time)	$T_g = T_j + kd^{0,55}$	?
Pprime	RCM (single shot)	Type-K : Ni/Cr	7,6 µm	Conduction error neglected	no correction	yes	yes	2 to 4 K (around +-10 ms relative to SOI)

Review of temperature measurement in ECN facilities

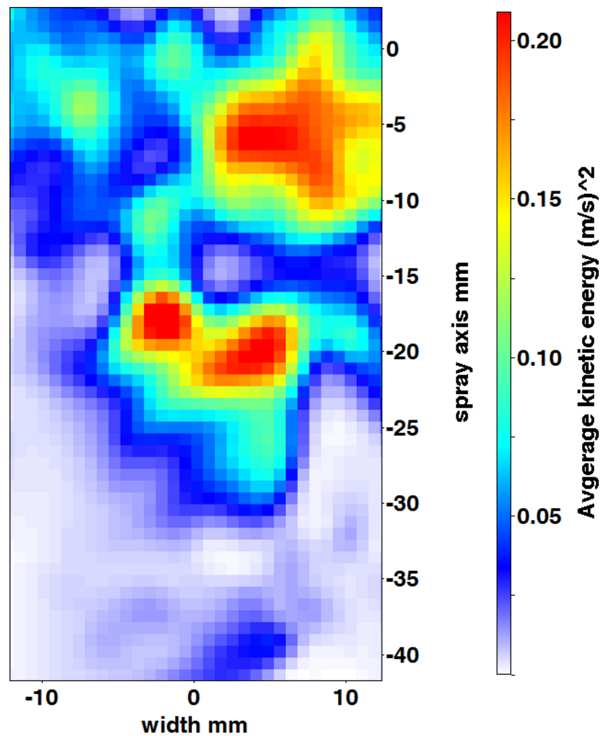
Comparison of data from literature

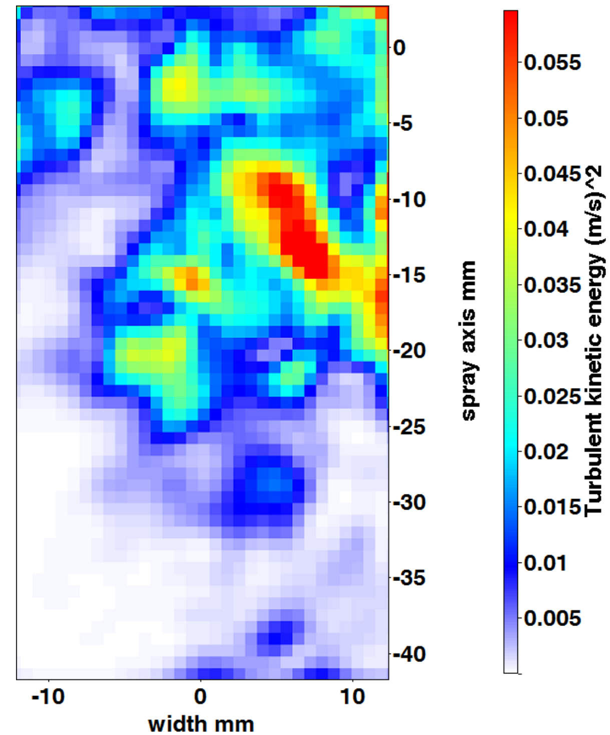
Institution	Facility	Thermocouple type	Wires dimension	Wall temperature	Heterogeneity level	reference
Sandia SNL	CVP	Type-R : Pt/Pt+13Rh	50 µm	461 K	* Std at 40 mm downstream of spray axis: 11 K * 45 K lower near the injector holder * +-1% variation in spray axis * +-4% variation in vertical axis +-15 mm	1- Meijer et al. Atomization and sprays, 22 (9) 2012 2- Pickett et al. SAE 2010-01-2106
TU/e	CVP	Type-R : Pt/Pt+13Rh	50 µm	443 K	* Std at 40 mm downstream of spray axis: 12 K	1- Meijer et al. Atomization and sprays, 22 (9) 2012 2- Pickett et al. SAE 2010-01-2106
IFPEN	CVP	Type-K : Ni/Cr	single 50 µm or 25 µm?	473 K	* Std at 40 mm downstream of spray axis: 14 K * +-2% variation in spray axis * < +-4% variation in vertical axis +-15 mm	1- Meijer et al. Atomization and sprays, 22 (9) 2012 2- Pickett et al. SAE 2010-01-2106
Caterpillar	CPF	Type-K : Ni/Cr	1 and 3 mm	800 +- 5 K	* 14 K lower near the injector holder (892 to 906 K within 3 mm from the injector)	1- Meijer et al. Atomization and sprays, 22 (9) 2012 2- Pickett et al. SAE 2010-01-2106
CMT	CPF	Type-K : Ni/Cr	?	800 +-5 K	* Std in center volume downstream of spray axis: 2,3 K (1 Hz logging) * 10 K lower near the injector holder (895 to 905 K within 3 mm from the injector)	1- Meijer et al. Atomization and sprays, 22 (9) 2012 2- Pickett et al. SAE 2010-01-2106
Pprime	RCM (single shot)	Type-K : Ni/Cr	7,6 µm	363 K	* Std at 39 mm downstream of spray axis: 20 K * spatial Std : 18 K	ECN France

Velocity data Pprime



Average velocity field
(time average 20 ms)
Maximum velocity 0,7 m/s





Turbulence is estimated in the time window -10 to +10 ms after SOI
It is possible to recalculate TKE with smaller time range or with cyclic variations but at a lower density level

Pprime RCM vs CMT RCEM